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WHERE WE STAND

...port of the AAF Scientific Advisory Group

BY

THEODORE VON KARMAN

The AAF Scientific Advisory Group was activated late in 1944 by General of the Army H. H. Arnold. He secured the services of Dr. Theodore von Karman, renowned scientist and consultant in aeronautics, who agreed to organize and direct the group.

Dr. von Karman gathered about him a group of American scientists from every field of research having a bearing on air power. These men then analyzed important developments in the basic sciences, both here and abroad, and attempted to evaluate the effects of their application to air power.

This volume is one of a group of reports made to the Army Air Forces by the Scientific Advisory Group.

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TABLE OF CONTENTS

INTRODUCTION

The present war started on both sides with "conventional" weapons and equipment; conventional because their principles of action, design, and performance were fundamentally known to the enemy. During the war both sides produced equipment and weapons of astonishing effects which will certainly change the whole picture of future aerial warfare.

This report is concerned with the main fields in which significant advances have been made and tries to show "where we stand" with some indications as to "where we shall go."

For future planning of research and development, the following new aspects of aerial warfare have to be considered as fundamental realities:

1. Aircraft, manned or pilotless, will move with speeds far beyond the velocity of sound.

2. Due to improvements in aerodynamics, propulsion, and electronic control, unmanned devices will transport means of destruction to targets at distances up to several thousands of miles.

3. Small amounts of explosive materials will cause destruction over areas of several square miles.

4. Defense against present-day aircraft will be perfected by target-seeking missiles.

5. Only aircraft or missiles moving at extreme speeds will be able to penetrate enemy territory protected by such defenses.

6. A perfect communication system between fighter command and each individual aircraft will be established.

7. Location and observation of targets, take-off, navigation and landing of aircraft, and communication will be independent of visibility and weather.

8. Fully equipped airborne task forces will be enabled to strike at far distant points and will be supplied by air.

It is too early to try to evaluate fully the influence of recent utilization of atomic energy on the conduct of aerial warfare. Therefore, such an evaluation is not attempted in this report. However, the development of this new source of energy will certainly make the supersonic airplane and the automatically guided pilotless aircraft even more efficient and will materially extend their ranges. Hence, the progress in utilization of nuclear energy will strengthen and accelerate the trends of aeronautical developments discussed in this report.

[illegible] topics [illegible] medical research, airborne armies, [illegible] in this report. [illegible] will be covered in my final report.

[illegible] all members of the Scientific [illegible]

WHERE WE STAND

SUPERSONIC FLIGHT

Supersonic flight appeared before 1940 as a remote possibility. Supersonic motion was considered as characteristic of artillery shells; level flight supported by wings was thought to be confined to the subsonic speed range. Some people talked of the stone wall against which we were running by trying to fly faster than sound.

One of the main results of bolder and more accurate thinking, and more experimentation in the last few years, is the fact that this stone wall disappeared, at least in our planning, and will disappear in actual practice if efforts are continued.

I believe the first engineering analysis presented in this country was contained in a report by myself and my collaborators early in 1944. It was shown in this report that an airplane of 10,000 lb gross weight, and 80 lb/sq ft wing loading, can climb to 40,000 ft altitude, reach a speed of 1000 mph, and fly at this speed for five minutes. As the propulsion device, a ramjet was considered.

The two main requisites of supersonic flight are the development of air frames which are aerodynamically efficient in the supersonic range and the development of lightweight efficient propulsion units.

The German contribution to the problem of supersonic flight is mainly on the aerodynamic side. No particular advance has been made by them in power plants such as the ramjet and turbojet for extremely high speeds. The Germans tested these power plants only at subsonic speeds Their main contributions to aerodynamics were as follows:

1. By wind-tunnel testing and by firing of winged missiles, it was shown that the passing of sonic velocity does not entail any stability difficulties if the transition is made in a relatively short time by rapid acceleration.

2. By wind-tunnel testing, it was found that efficient wing forms with high lift over drag ratio and effective control surfaces could be designed for supersonic flight.

These German achievements are not the result of any superiority in their technical and scientific personnel, however, but rather due to the very substantial support enjoyed by their research institutions in obtaining expensive research equipment, such as large supersonic wind tunnels, many years before such equipment was planned in this country.

SUPERSONIC WIND TUNNELS

There is no doubt that we were slow in recognizing the necessity of supersonic wind tunnel research. [illegible] the Chief of Ordnance, [illegible] from a trip to Europe in 1937, to install a supersonic tunnel at Pasadena. General Barnes decided in 1942 to build such a tunnel at Aberdeen Proving Ground. The design was based on model studies carried out between 1940 and 1942 at the California Institute of Technology. Wright Field and NACA are building supersonic wind tunnels but until recently only one small tunnel with a cross section of 7.5 x 7.5 in. was available. As the missile program made the need for supersonic aerodynamic data urgent, the Budget Bureau of the Government ordered hearings with the idea rather of restricting than encouraging the construction of such vital instruments of research under the slogan of "avoid duplications."

The picture of the situation on the other side is given by Figs. 1 and 2, which cover German supersonic wind tunnels in operation and under construction.

It seems to me that the Air Forces have to recognize the fact that the science of supersonic aerodynamics is no longer a part of exterior ballistics but represents the basic knowledge necessary for design of manned and unmanned supersonic aircraft. The Air Forces have to provide facilities and include this field in their research, development, and training programs.

ARROWHEAD WING

The main difficulty of flying at speeds near and beyond the velocity of sound is, of course, the extremely low lift-drag ratio of the airplane due to excessive drag. The range of an airplane, for example, is directly proportional to this ratio. Wing theory and wing design for subsonic airplanes were worked out with rather surprising success in this country and we were ahead of the Germans in this field. However, in the field of transonic and supersonic wing design, the Germans developed to the point of practical application ideas which were only in the discussion stage here.

The optimum lift-drag ratio of the wing of a very well designed subsonic airplane, the Mustang, is shown in Fig. 3. It is seen from the same figure that the lift-drag ratio for a rectangular supersonic wing at a Mach number of 2 is less than that of an old-fashioned biplane cell. This is the point where new ideas must step in.

One such idea is that of the arrowhead wing (Pfeilflügel), first suggested in a scientific paper by A. Busemann in 1935. This was a dormant idea until revived with success by German scientists and designers in the period 1942-1945.

The arrowhead wing is based on the thought that sweeping back the wings reduces considerably the effective Mach number of the wing and so lowers the resistance. As a matter of fact, if the sweepback is sufficiently large, the shock wave can be eliminated even at supersonic speeds over the greater part of the wing. I include here two photographs (Fig. 4) which belong to a series of experiments carried out at my suggestion in the Aberdeen supersonic wind tunnel in April, 1945, before I went abroad. These experiments were made at a Mach number of 1.72. It is seen that the straight wing produces a strong shock wave at the leading edge which fails to appear in the case of the swept back wing. Robert Jones of the NACA announced similar suggestions in a report in June, 1945. The German scientists carried out comprehensive investigations on the problem. The two lower illustrations in Fig. 3 show the improvements of lift-drag ratio which can be realized by proper wing shapes. The Germans found that the reduction of the effective Mach number by sweepback applies also to

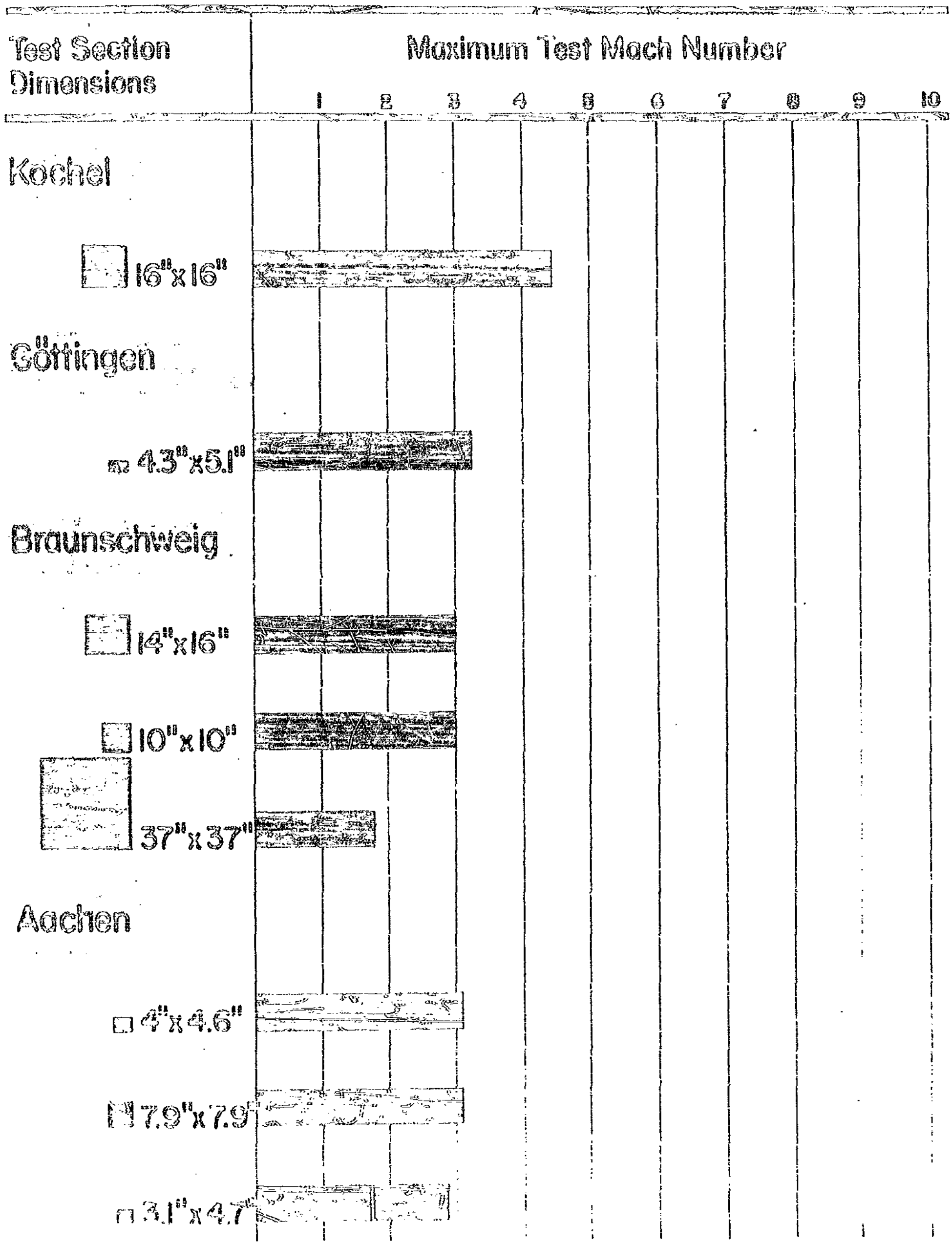


Figure 1 — German Supersonic Wind Tunnels (operation 1945)

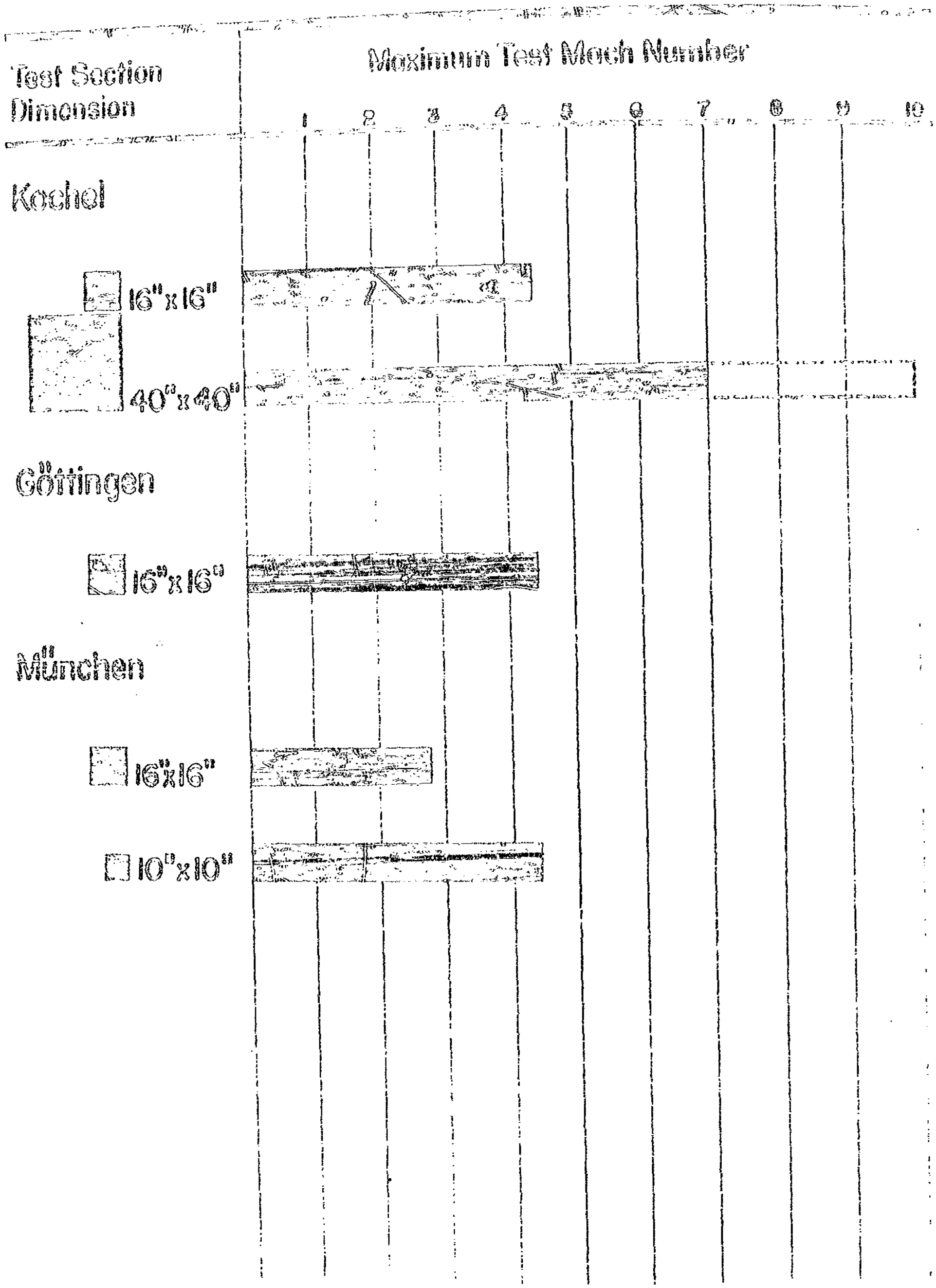


Figure 2 — German Supersonic Wind Tunnels (Construction 1945)

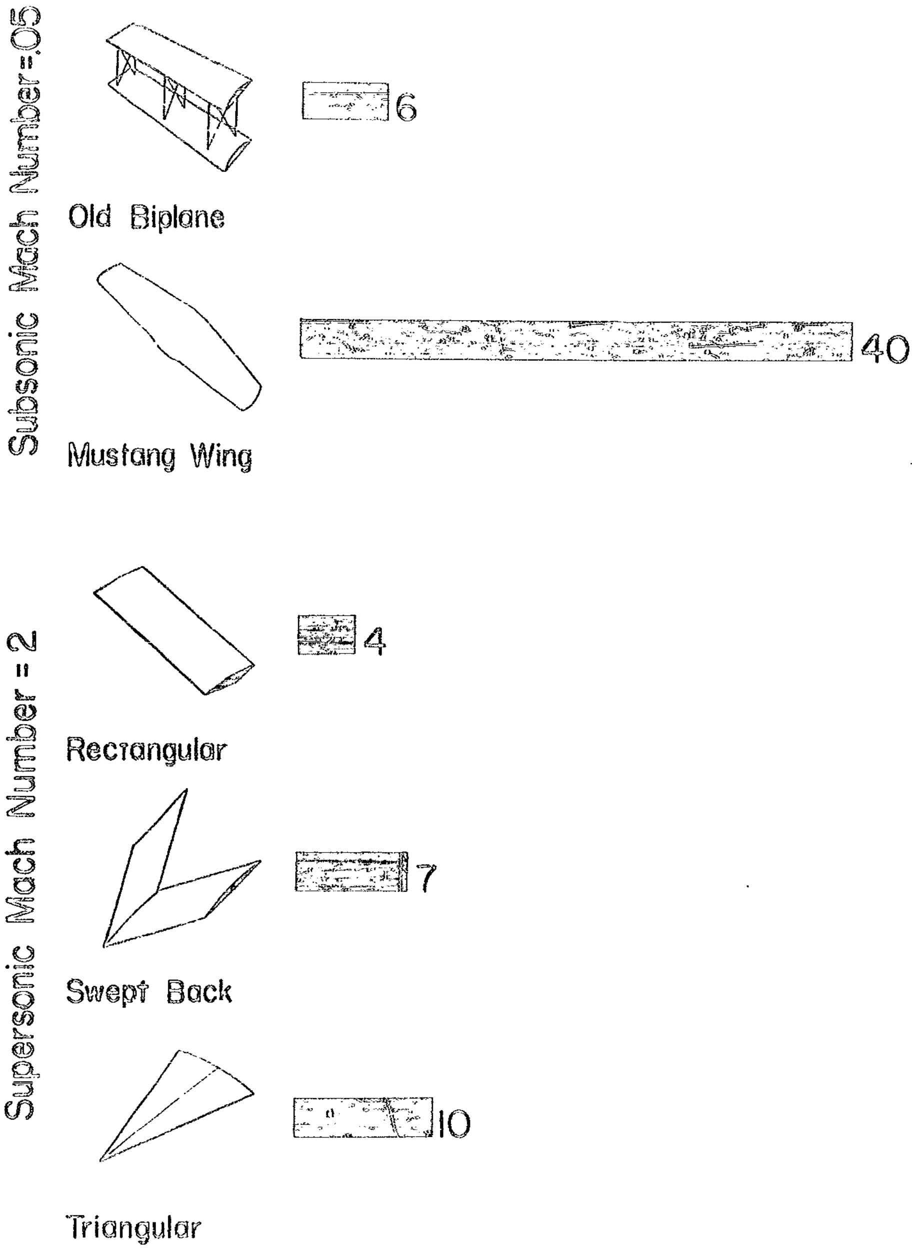


Figure 3 — Optimum Lift-Drag Ratios

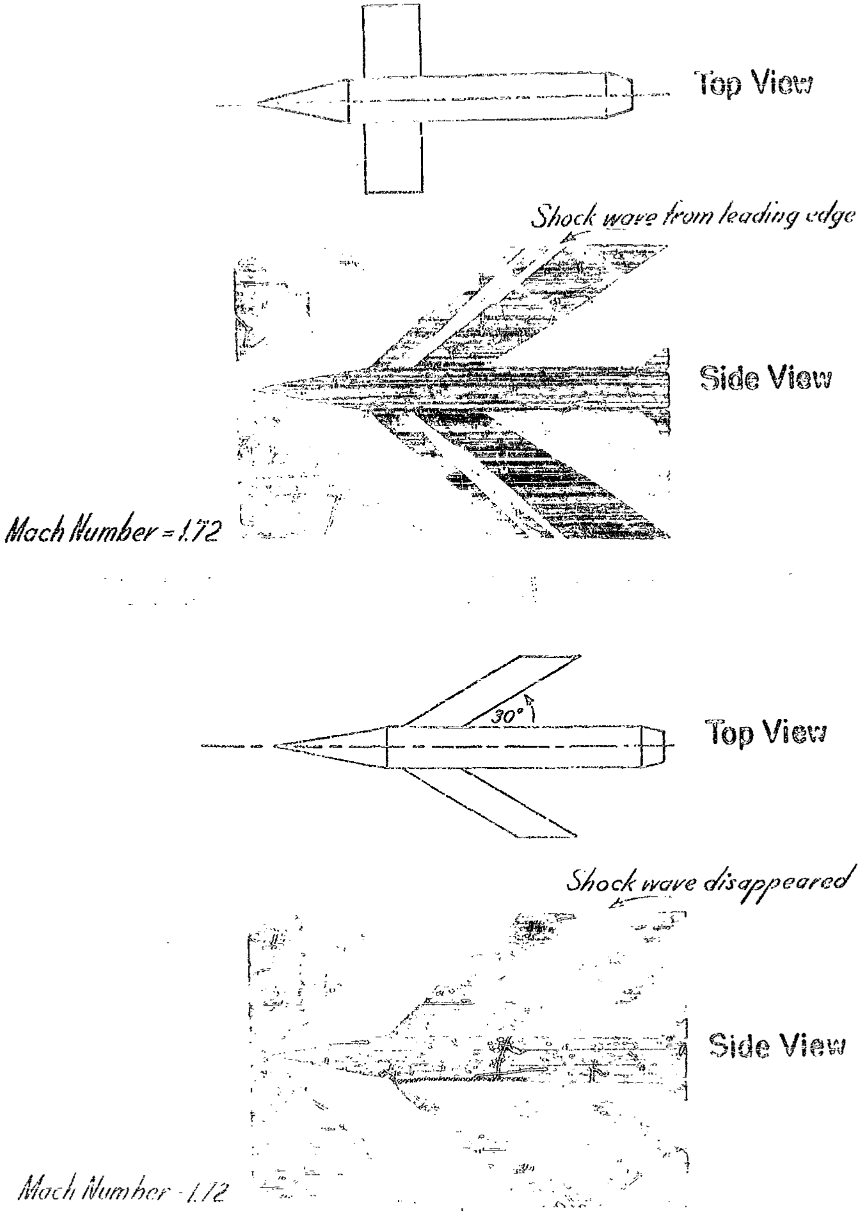


Figure 4 — Sweepback Effect on Shock Waves

the transonic range. They found that the critical Mach number at which the compressibility effects increase the drag and cause stability troubles, can be pushed to higher values by large sweepback of the wings. This result was utilized in several of their last airplanes, for example, the Messerschmitt-Lippisch design of their rocket interceptor, the Me-163.

SUGGESTIONS FOR RESEARCH

I believe that for the realization of supersonic flight, the following engineering researches are indicated:

1. Complete airplane models with actual operating power plant should be tested for performance and detailed improvements in supersonic wind tunnels at supersonic speeds. For this purpose supersonic wind tunnels of large test sections are necessary so that not only the components, such as wing and fuselage, but a whole airplane as well can be studied for optimum design.

2. Since wind-tunnel testing in the speed range in the immediate neighborhood of the sonic velocity is unreliable, research in this speed range should be supplemented by special flying research airplanes in order to obtain performance data as well as flow mechanics data at high speeds. For the success of these tests, a complete, careful instrumentation and flight-testing technique has to be developed so that accurate and detailed flow information can be obtained.

3. Methods of launching the airplane by various auxiliary power plants, such as rockets, should be investigated. One promising means of launching is to combine the take-off and climb into one single step by rockets as shown in Fig. 5. The transition through the velocity of sound will be then very fast and the rockets can be dropped when spent. No long runways will be necessary and the main power plant, turbojet, or ramjet, can be designed most efficiently for supersonic operation only.

4. Landing is facilitated by the fact that the fuel consumed is a large percentage of the initial weight. However, to enable landing at a safe low speed, deceleration and lift increase by appropriately directed rocket thrust during the last few seconds of descent may be necessary, as shown in Fig. 5. This method of landing has to be studied.

Only through such a program of research can the problem of supersonic flight be satisfactorily solved. Of course, from the point of view of tactical usage of supersonic aircraft, the result of this research program is only the first step. There still remains the question of working out the best ways of using an aircraft of supersonic speed for the different situations. However, the very new horizon opened up by a velocity higher than sound justifies the intensive research indicated. We cannot hope to secure air superiority in any future conflict without entering the supersonic speed range.

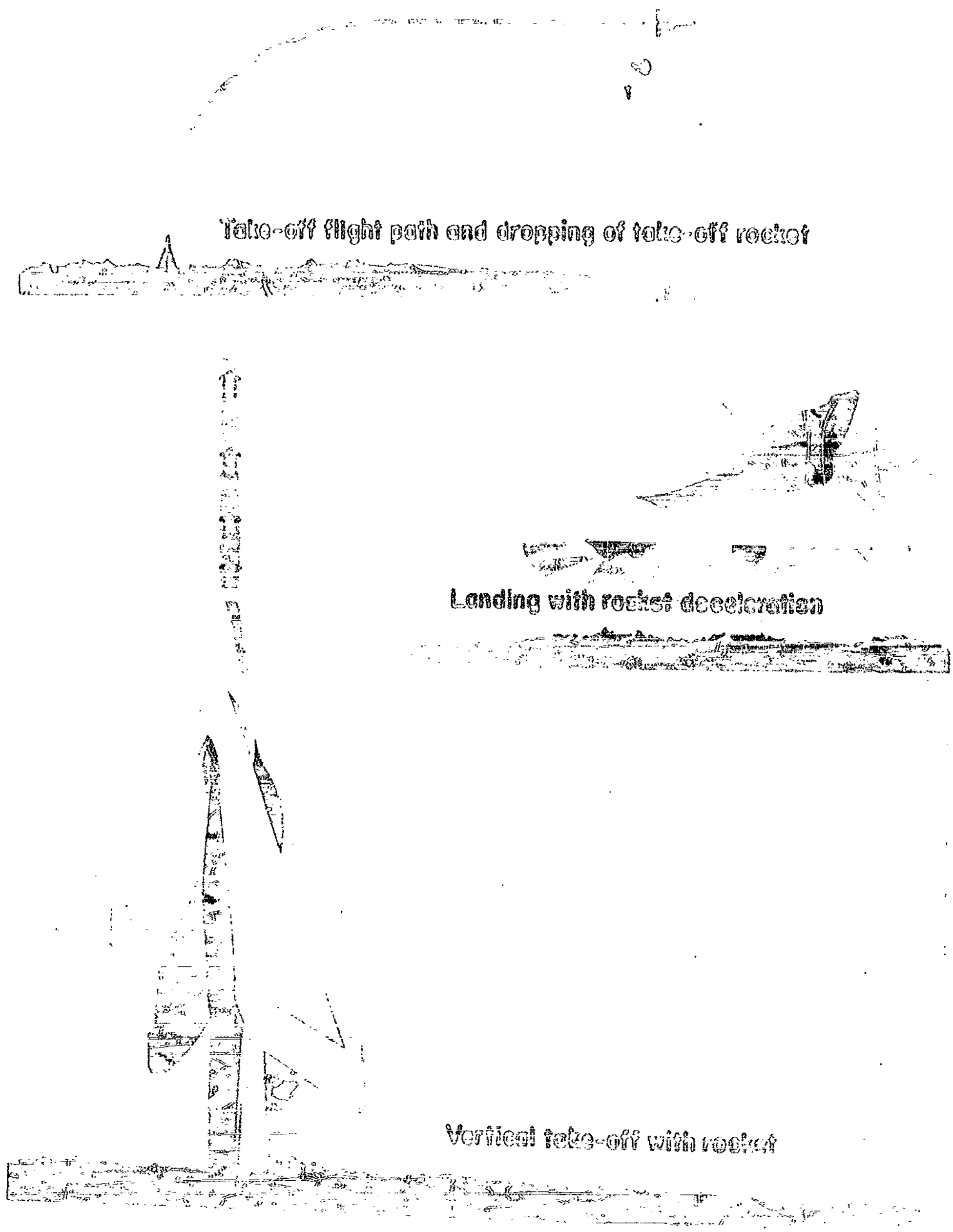


Figure 5 — Supersonic Airplane: Take-off and Landing

PILOTLESS AIRCRAFT

GERMAN DEVELOPMENT OF GUIDED MISSILES AND PILOTLESS AIRCRAFT

The German effort on guided missiles and pilotless aircraft was aimed at three tactical problems: (1) the bombing of Allied ships, both naval and merchant vessels; (2) long-range strategic bombing of England; and (3) defense against Allied bombers. Some thought and effort had also been given to the problem of the long-range strategic bombing of America by unmanned missiles.

Development of high-angle and glide bombs to answer the first problem was started about the end of 1939 or the beginning of 1940 and resulted in the PC-1400-FX and Hs-293 missiles, first used in August and October, 1943. Both missiles were direct-sight radio-controlled and became unusable as soon as air superiority was lost.

The well-known V-1 and V-2 were used to meet the second problem, which arose after the failure of the attempt to bomb England by conventional aircraft because of the efficient British air defense. Although the fundamental scientific research and development work on these missiles had its root in projects initiated for other purposes as early as 1935, the focusing of effort on the tactical problem of long-range bombing of England appears to have started in 1941.

The history of development of the buzz-bomb (V-1) is quite interesting. An inventor, Paul Schmidt, had a development contract from the Air Ministry for an intermittent jet motor in 1935. The work proceeded slowly. About November, 1939, Diedrich, of the Argus Motor Company, who had been working for the Air Ministry on exhaust pipe jet-propulsion nozzles, began work on intermittent combustion in an open pipe. In 1940, the Air Ministry brought Schmidt to the Argus Company and combined the developments. The first successful motor was completed in 1941. This motor development itself was intended for use in aircraft. About that time the ground forces development of the large V-2 rocket, which was started at a very early date, was delayed. Since this weapon was considered extremely important for the outcome of the war, an official of the Air Ministry proposed the use of a combination of small airplane with intermittent jet motor as a substitute for the same purpose. The V-1 was thus conceived and became a development of the air forces. Its code name was originally Kirschkern (cherry pit) because it was merely to be spit out against England.

Fieseler Aircraft Company was selected to build the air frame. The development tests were made at the Air Ministry laboratory at the Luftfahrtforschungsanstalt Hermann Göring, Braunschweig, in the 2.8-m high-speed wind tunnel. The original model of the V-1 was not very good, the net thrust of the motor being zero at 380 mph. About 60% of the operating time of this wind tunnel was needed for nearly a year to bring the development to its present stage.

The first reconnaissance photograph of the V-1 was taken by the British at Peenemünde in April, 1943, and bombing made Peenemünde uninhabitable by August, 1943. The first operational use of the V-1 was on 12 June 1944.

The V-2 or long-range rocket was known as A-4 or Apparat 4. The first of the series, A-1, was fired in 1935 at Kummersdorf. It was a small rocket of aluminum construction, 100-kg thrust, intended for use on aircraft.

Dr. von Braun, leader of the Peenemünde group which developed the V-2, was a student of Professor Hermann Oberth, a well-known inventor and writer in the field of rockets, who had published books on interplanetary rocket travel. A group of Oberth's students became interested in rockets and organized an amateur rocket group. All were well-trained scientists. In 193[illegible], Dr. von Braun was employed by the German War Department and sent to Peenemünde. In 1941, von Braun brought Oberth there as head of the Patent Section. By 1941, Peenemünde was an active test station. The Me-163 was brought there in September, 1941 and in October, 1941 flew at a speed of 1003 km/hr (about 623 mph). In October, 1941, the first supersonic wind-tunnel tests were made on a projectile at a Mach number of 4.4. After the bombing of Peenemünde in August, 1943, the activities were decentralized. The wind-tunnel group went to Kochel, where it was in operation in January, 1944. The first use of the V-2 was on 8 September 1944.

Development of guided-missile defense against bombers began early in 1943. The missiles were all rocket-propelled and, in their final development, many were to be automatically controlled with homing devices and equipped with proximity fuses. Many of these missiles (X-4, Hs-298, Schmetterling, Rheintochter, Enzian, and Wasserfall) reached their final testing and early production stage but with direct-sight radio-control only. The electronic developments, homing devices, and proximity fuses lagged behind the vehicle and propulsion unit developments. The X-4 air-to-air missile was provided with an interesting direct wire control to avoid the possibility of jamming, present with radio control. Two of the wings carry at the tips spools of fine wire, long enough to permit a range of three miles while maintaining direct wire connection between the missile and the control aircraft. The wires can be fed out at speeds of more than 400 mph. None of these missiles were used against our bombers. The German situation became so critical indeed that development of complicated guided rockets was stopped in February, 1945, in favor of concentrating on small, unguided rockets to be used in large numbers.

The German military agencies, research institutions, and industrial designers devoted a large effort to guided missiles and considered them very promising weapons. In August, 1944, there were some 25 projects for homing devices under development. The major research laboratories of the air and ground forces made many wind-tunnel and flight tests, some at high supersonic speeds, and made many theoretical studies of problems related to guided missiles and pilotless aircraft.

Perhaps the most important result of the German effort in this field was to show that winged missiles are superior in performance to finned missiles. Thus, the next stage in the development of the V-2 rocket was to have been the addition of wings. The necessary wind-tunnel tests had been made in connection with the development of the winged ground-to-air rocket Wasserfall and ballistic computations had shown that this change alone would increase the range of the V-2 rocket from about 250 to about 400 miles. Wind-tunnel models of the winged V-2, known as A-9, are shown in Fig. 7.

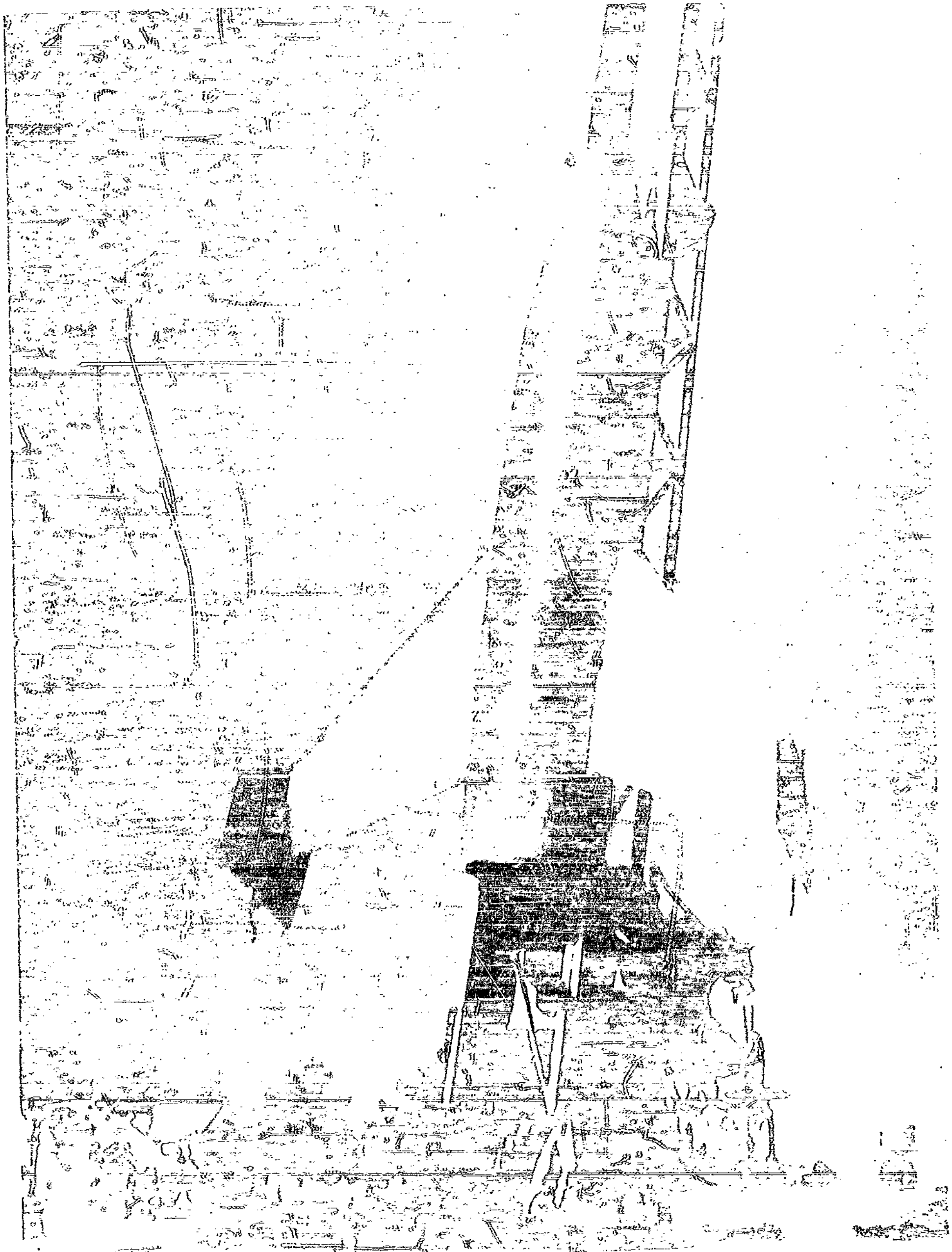
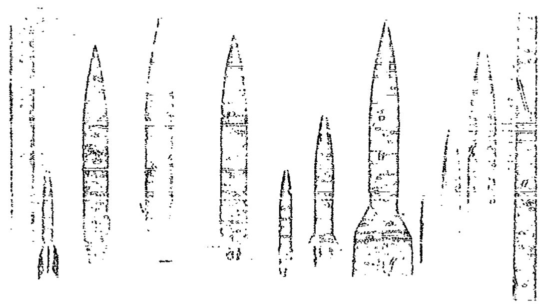
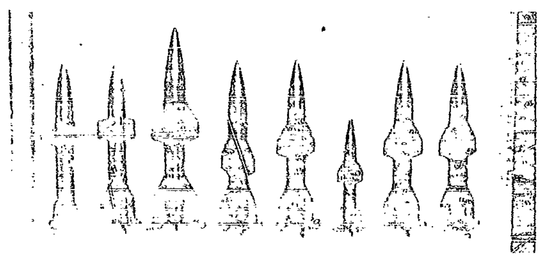


Figure 6 - - German "Feuerlilie" Rocket

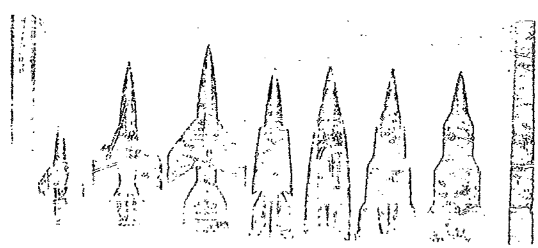
Original V-2 Rocket



Wasserfall Rocket



V-2 Rocket with Wings



V-2 Rocket with Wings

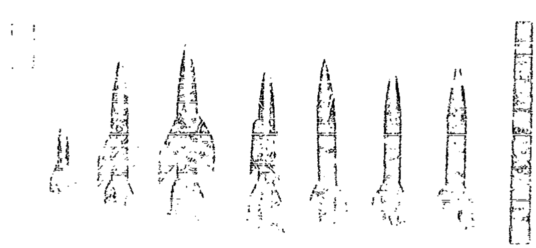


Figure 7 — Rocket Models for Supersonic Wind-Tunnel Tests

The German scientists believed, although some German engineers in industry disagreed, that the ultimate guided missile would be completely automatic in its operation. Although for quick development and for test purposes they favored the use of manual radio control, their long-range plans contemplated first automatic blind tracking of the missile and target, then the connection of the two tracking devices through a computer to the radio control channels, and finally the use of a homing device for the last part of the trajectory and a proximity fuse.

Looking over the great variety of projects one finds that the V-2 rocket was the most outstanding technical achievement and that the Peenemünde group of scientists, working for the ground forces, was the most capable missile research group in Germany. It is important for us to note that one element in their success was the fact that they had under a single leadership in one organization, experts in aerodynamics, structural design, electronics, servomechanisms, gyros and control devices, and propulsion; in fact, every group required for the development of a complete missile. The letters and papers in the files of industrial groups, like Messerschmitt, show rapid progress in the field of vehicle and propulsion, the fields in which the firm itself had qualified people, but delay after delay on controls and electronic devices which had to be secured elsewhere. The Luftwaffe research laboratories made little progress in the actual development of specific weapons, largely because of the absence of electronics experts and their lack of facilities for the construction of experimental missiles.

In addition to the German view that the final guided missile would be completely automatic in operation, the possibilities of long-range strategic bombing were fully understood. There is no question but that the diversion of the efforts of the Peenemünde scientists in 1943 to the development of an antiaircraft guided rocket delayed the introduction of the winged V-2 rocket (A-9) and its successor, the transoceanic rocket (A-9 plus A-10). Drawings and computations had been completed for the A-10, a rocket weighing 85 T with a thrust of 200 T to be used as a launching rocket for the A-9, accelerating it to a speed of 3600 ft/sec. The motor of the A-9 would accelerate it further to a speed of 8600 ft/sec, giving it a range of about 3000 miles. Some consideration was given to the design of one version of the A-9 carrying a pilot. The Scientific Advisory Group agrees that the German results of wind-tunnel tests, ballistic computation, and experience with the V-2 justify the conclusion that a transoceanic rocket can be developed.

The principal German advantage in the field of guided missiles was the lead in time in the development of rockets, which were considered to have serious military applications as early as 1935. Much effort was put into this field and as a result the supporting industrial developments were ready as a foundation for missile designers. They could buy rocket motors and rocket fuels from commercial sources. In this respect they lead us. The V-2 development was successful not so much because of striking scientific developments as because of an early start, military support, and a boldness of execution. In the electronic field, radar in particular, we are definitely one or two years in the lead, although we have not put as much effort in the experimental determination of the limits of application of acoustic and infrared devices.

PILOTLESS AIRCRAFT FROM VIEWPOINT OF THE AIR FORCES

The Air Forces have rather thoroughly explored the field of guided high-angle and glide bombs released from aircraft. This program is undoubtedly well known to the Commanding General through the AMC progress reports. It includes preset glide bombs controlled by an automatic pilot, high-angle and glide bombs remotely controlled by radio with and without television repeat-back equipment, and high-angle and glide bombs homing by light, heat, and radar. During the war period there were many projects and the number tended to grow continually. In this early stage of development there was not much possibility for real systematic planning. It should be possible now to reduce the number of projects to those meeting definite military requirements and to standardize on a small number of missiles. These standardized missiles should be used to continue research and development on homing devices.

Our endeavors in pilotless aircraft in the proper sense include, in addition to the successful reproductions of the V-1 type, a few promising beginnings. However, the Air Forces should realize that the task is far beyond the scope of inventing gadgets and trying to make them work. There is urgent need of a systematic analysis of the various tasks which manned airplanes equipped with bombs, guns, and rockets perform, and which now may be performed by pilotless craft.

In other words, two developments have to meet for successful solutions of the problems: The tactical viewpoint must lead to the choice of the types of pilotless aircraft; on the other hand, physical science will proceed to offer more and more extended ranges and improved accuracy.

However, beyond that the implications of the accomplishments of the German Peenemünde group and of the recent development of the atomic bomb by United States and British scientists, future methods of aerial warfare call for a reconsideration of all present plans. A part, if not all, of the functions of the manned strategic bomber in destroying the key industries, the communication and transportation systems, and military installations at ranges of from 1000 to 10,000 miles will be taken over by the pilotless aircraft of extreme velocity. The use of supersonic speeds greatly reduces errors due to wind drift and other atmospheric conditions and the tremendous zone of damage of the atomic bomb diminishes the required precision. Hence, the difficult control problem is made easier.

For the future long-range strategic bomber, the Scientific Advisory Group foresees two types of pilotless aircraft, both with wings, one with a high trajectory reaching far into the outer atmosphere, and the other designed for level flight at high altitudes. The first one can be considered as a further development of the V-2 rocket. In fact, this was planned by the German scientists. By using two or more step-rockets for the acceleration, a very high speed is imparted to a missile, perhaps as high as 17,000 mph or more, to give ranges of several thousand miles. In this case, the wings are required mainly for control purposes, but they also serve to extend the glide path in the lower atmosphere. The German scientists have suggested a second type of trajectory, requiring less initial energy, in which the wings are caused to curve the path of the missile when it returns to the region of increasing air density so that it rebounds to great heights. After a number of rebounds the winged missile settles down to a steady glide. Such a trajectory would seem difficult to control accurately.

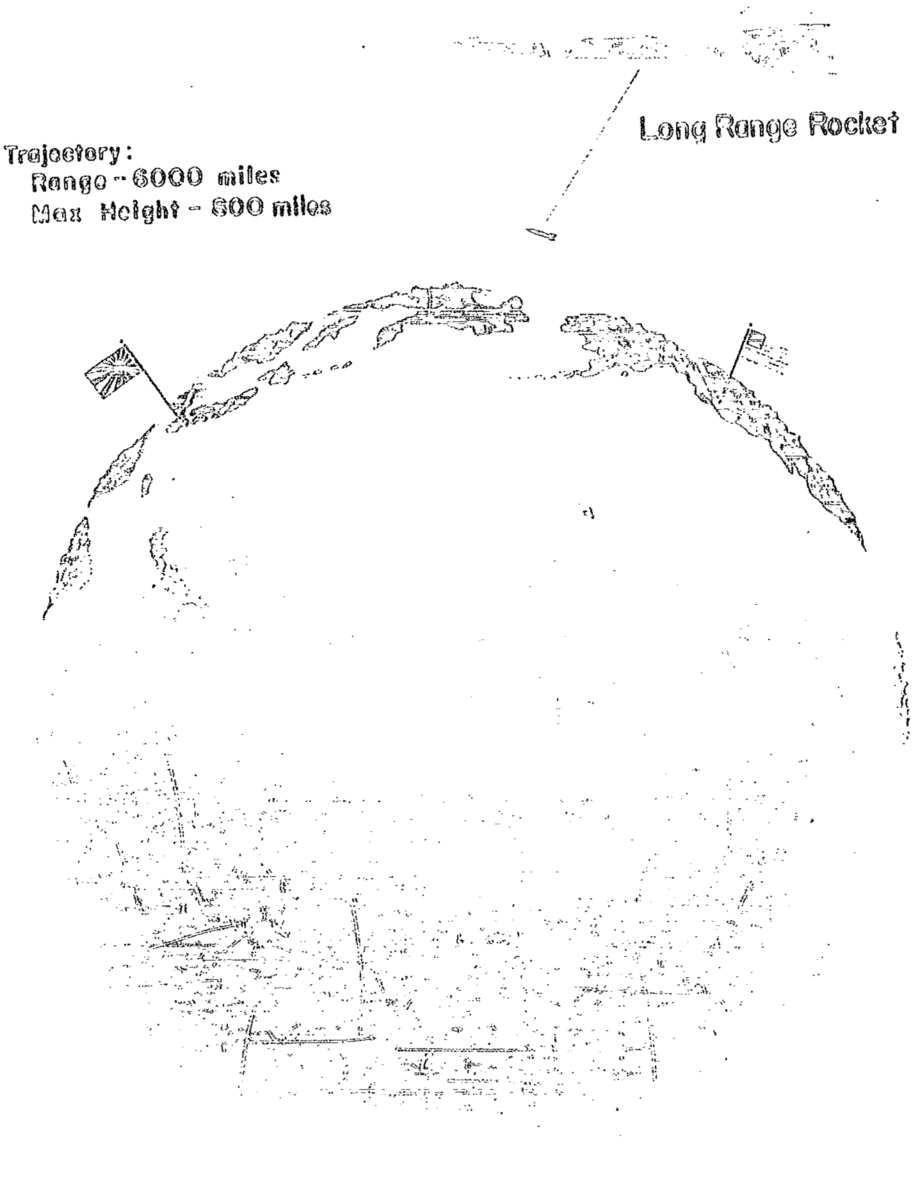


Figure 8 — 6000-Mile Rocket

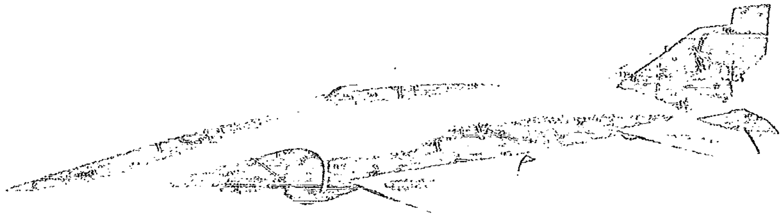
The second future strategic bomber is a supersonic pilotless aircraft, flying at altitudes of from 20,000 to, say, 60,000 ft. It appears to us now that the speed will be about twice the speed of sound and that the aircraft will be powered by a turbojet motor. An intermediate step might be a pilotless aircraft traveling at high subsonic speeds with a Mach number of about 0.9 about 600 mph at 40,000 ft.

For the future defense against hostile aircraft, it seems clear that supersonic guided missiles will be used, propelled either by rockets or more probably by a ramjet. The fully automatic radar beam-guiding methods of control of the type suggested, but not experimentally tried, by the Germans will probably be used for guiding, supplemented by simplified heat-homing devices and proximity fuses.

The present facilities and organization for research and development of pilotless aircraft appear inadequate. It cannot be expected that such complex problems can be successfully solved by any group which is specialized in only one of the several fields which are involved.

Leadership in the development of these new weapons of the future can be assured only by uniting experts in aerodynamics, structural design, electronics, servomechanisms, gyros, control devices, propulsion, and warhead under one leadership, and providing them with facilities for laboratory and model shop production in their specialties and with facilities for field tests. Such a center must be adequately supported by the highest ranking military and civilian leaders and must be adequately financed, including the support of related work on special aspects of various problems at other laboratories and the support of special industrial developments. It seems to us that this is the lesson to be learned from the activities of the German Peenemünde group.

Supersonic Pilotless



P-80; Subsonic

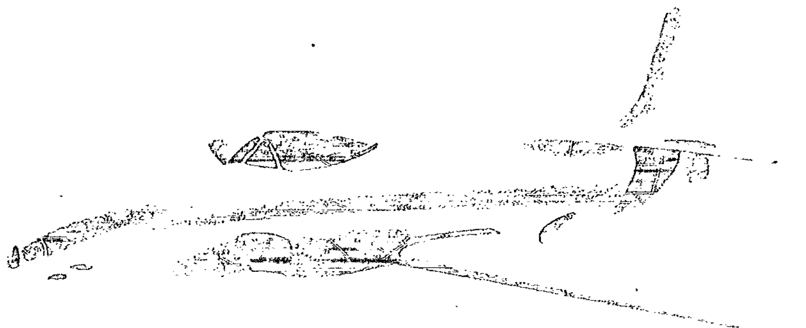


Figure 9 — Supersonic and Subsonic Airplanes

PROPULSION METHODS IN THE MAKING

INTRODUCTION

The following classification embraces the most important novel methods of propulsion emerging from the war years, utilizing atmospheric oxygen:

	Suggested Designations	*German Designations*
Reciprocating engine + ducted fan........................	Motorjet	ML
Gas turbine + propeller........................	Turboprop	PTL
Gas turbine + ducted fan........................	Turbofan	ZTL
Gas turbine + jet........................	Turbojet	TL
Continuous jet, compression by aerodynamic ram........................	Ramjet	L
Intermittent jet........................	Pulsojet	IL

These systems are shown schematically in Figs. 10a and 10b.

The motorjet is widely known as the Campini system. As a matter of fact such a propulsion system was used in the first jet-propelled airplane which was flown in Italy a few years before the war. Probably it will be found heavier and less efficient than some other systems. All elements of the various systems were known long before the war in the patent literature. The fact that they succeeded in becoming practical realities is due to several causes:

1. Fast airplanes and missiles required propulsion systems independent of the use of propellers.

2. Military use justified the design of engines with relatively poor fuel economy, if they are lighter and less bulky than conventional reciprocating engines and/or could offer themselves to simpler manufacturing methods.

3. The science of aerothermodynamics, especially research on combustion in high-speed airflow made great progress in the war years.

4. Metallurgy found new high-temperature-resisting materials.

5. Bold and progressive designers created prototypes of turbines and compressors which conventional engineering considered impossible.

The progress made in combustion technique, lightweight construction, and materials is here to stay and development will continue. In addition, proper scientific study and further research will make at least some of the new propulsion systems equally or more economical than the conventional engines are now. On the other hand it may also happen that the competition of the novel ideas will induce designers of reciprocating engines to produce some radical improvements in their own field. In the following pages, Allied and German developments in the new propulsive devices are

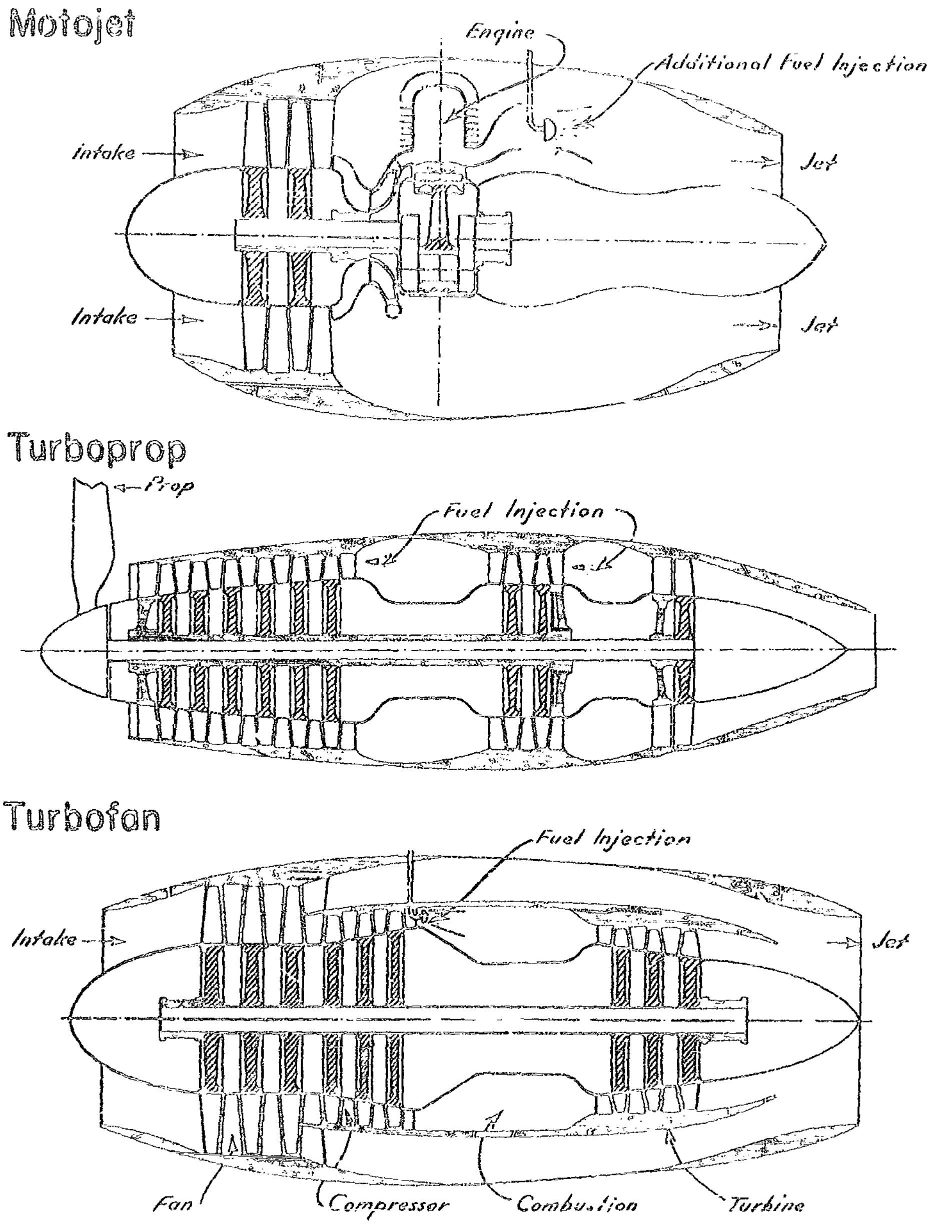


Figure 10-A — Various Propulsion Systems

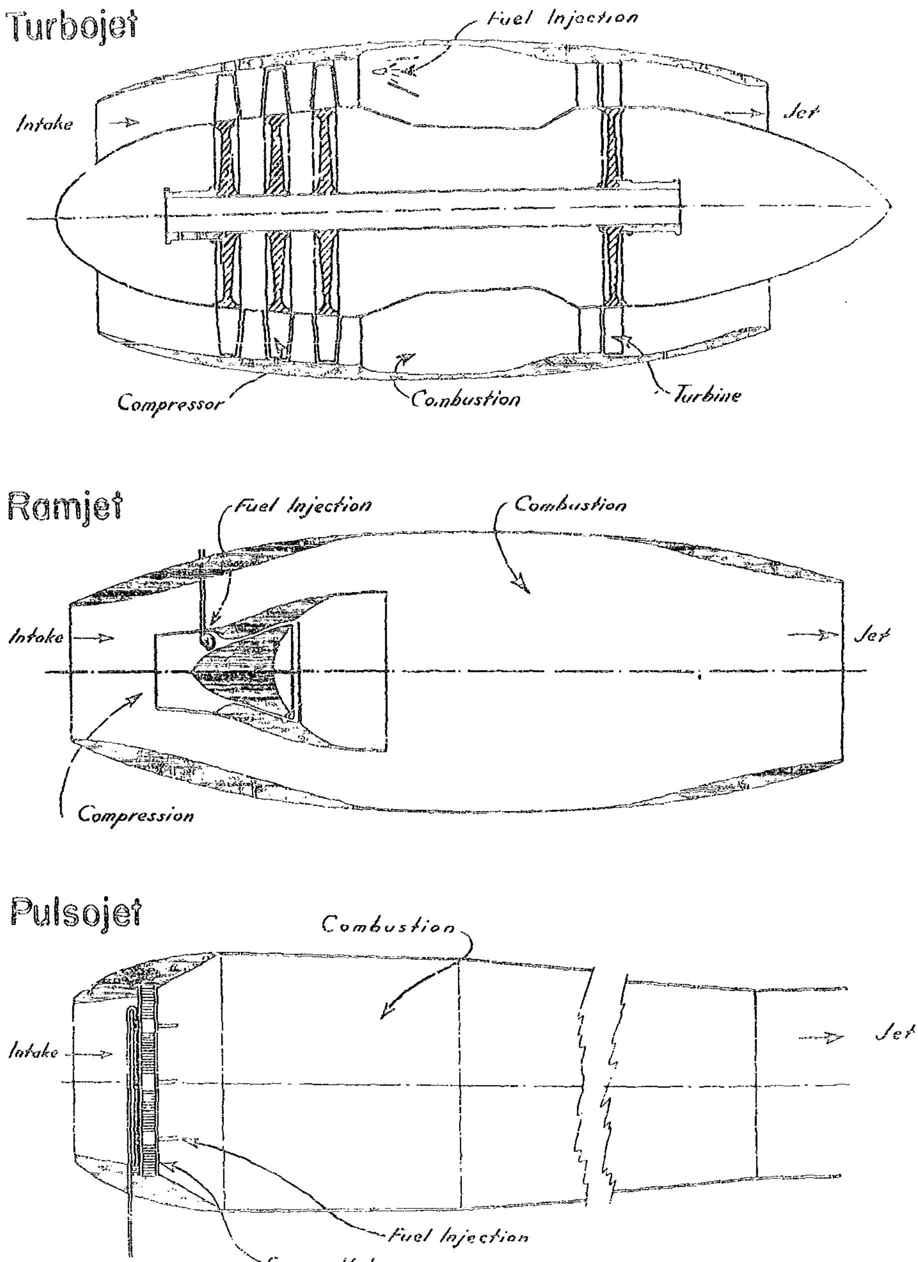


Figure 10-8 · – Various Propulsion Systems compared in some detail. Before discussing the most important types, I include here as a matter of interest a 12-year plan for the period 1938-1950, which the man responsible for engine research in the German Air Ministry published in a secret document in July, 1943, although it does not appear to me as a very well-balanced and far-seeing project.

First 4-Year Program (1938-1942). The aim of the first 4-year program was the development of simple turbojet engines for mass production, without particular regard for quality, utilizing readily available material, simple manufacturing methods, and generous tolerances. At the same time studies were to be initiated in preparation for the second period. Results of the first period are shown in mass production of turbojets such as the BMW 003, the Jumo 004, and the Heinkel-Hirth 011.

Second 4-Year Program (1942-1946). This period had the objective of developing the following items:

1. Improved turbojets of higher power, capable of operation at higher altitudes. (Example: BMW 018 for 7700-lb thrust.)

2. Gas turbine + ducted fan units.

3. Gas turbine + propeller combination. (Example: BMW 028 for 12,000 hp at 500 mph at sea level.)

4. Ramjet.

5. Research and design studies on a gas turbine with heat exchanger for long distance flights. This has the German designation GTW.

6. Reciprocating engine + ducted fan units.

7. Research and development on the explosion-type gas turbine. One of the ideas on this subject was the use of a pulsojet, such as the V-1 motor, as a source of gas for operating a turbine.

Third 4-Year Program (1946-1950). Development to a working state of the following items was visualized for this period:

1. Gas turbine with heat exchanger (GTW system).

2. Reciprocating engine + ducted fan units.

3. The intermittent or explosion-type gas turbine.

TURBOPROPELLER AND TURBOFAN

It is general opinion that simultaneously with the development of the jet reaction principle for fast airplanes the gas turbine with propeller or fan drive will have wide applications for airplanes of moderate speed. Jet propulsion has intrinsically low efficiency at low and moderate speeds so that the propeller is superior. On the other hand, it is expected that further research will help the gas turbine attain at least the same efficiency as reciprocating engines now have. It will then have the additional advantages of lighter weight, simpler construction, and absence of the vibrations inherent in reciprocating engines.

The thermal efficiency of existing gas turbines is still considerably lower than that of reciprocating engines at their optimum operating conditions. However, many methods not yet completely developed are available for improvement of the efficiency and associated reduction of fuel consumption of the gas turbine. Heat exchangers help to recover the energy of hot exhaust gases; intercooling between compressor stages and reheating between turbine stages increase the cycle efficiency. Finally, the replacement of the rotating compressor and combustion chamber by a reciprocating system, for example, a free-piston gas generator, allows the use of high pressures and materially lowers the fuel consumption. It is extremely desirable that all of these avenues of further improvement be thoroughly investigated. An interesting German suggestion, a free-piston gas generator with doughnut-shaped housing for the pistons, is shown in Fig. 11. The arrowhead-wing principle applied to the design of high-speed propellers for reducing compressibility effects and increasing efficiency is also shown in Fig. 11. Table I outlines German and Allied turboprop and turbofan, and high-speed propeller developments.

TURBOJET

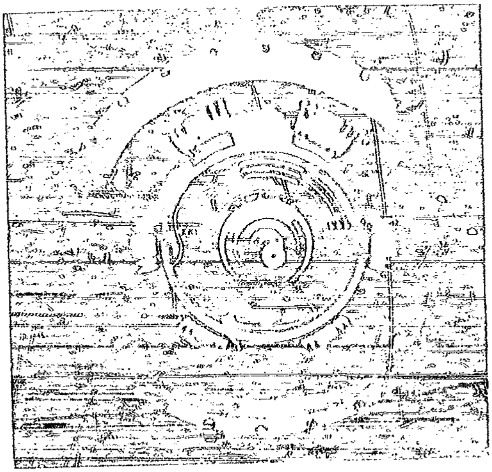
The principles and main design characteristics of turbojet engines for airplanes were known before the war in all countries. Endeavors in private industry in England and Germany started at about the same time, in 1935. Our own industry was somewhat discouraged by official studies which were certainly much too conservative, especially concerning the weight of gas turbines and compressors. The German government was perhaps more alert in subsidizing this development than was the English government. The American development started with directives from General Arnold. As far as the centrifugal type of compressor is concerned, the U.S. units were based on Whittle's design, utilizing our own experience with turbosuperchargers. The independent development of the axial-type compressor started about the same time. In the German designs, both centrifugal and axial types are used; with emphasis on the axial. The progress of the actual prototypes in Germany is illustrated by a timetable taken from a German report, dated 2 November 1944, shown in Fig. 12.

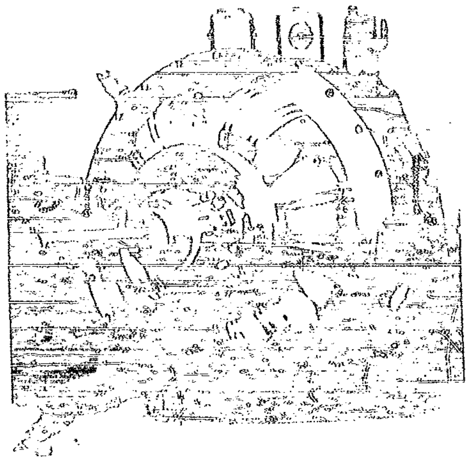
The comparative merits of Allied and German turbojet units are shown in Fig. 13. It is seen that the Germans were ahead as far as the sizes of units are concerned; but they were trailing slightly both in specific weight of the engine and in its specific fuel consumption.

In Table II, I am including a list of detailed research problems which may be helpful for planning future research in the field of gas-turbine and jet engines, as well as in the field of turbojets. None of these problems was solved in Germany with decisive success; but most of them were carefully studied in German laboratories. The status of German research is indicated with some remarks concerning the outlook and recommendations.

The present application of turbojet engines is for propelling airplanes at the upper end of the subsonic range. Although the propulsion efficiency of the jet is relatively low at such flying speeds, its application is justified by lightness of weight and simplicity of construction of the jet engine in comparison with reciprocating engines, and because the efficiency of propeller drive decreases somewhat at flight speeds approaching sonic velocity. On the other hand, the propulsive efficiency of jet drive is increasing with increasing flight velocity; hence, we have to consider the possibility of using the

Free-Piston Engine





Swept-Back Propeller

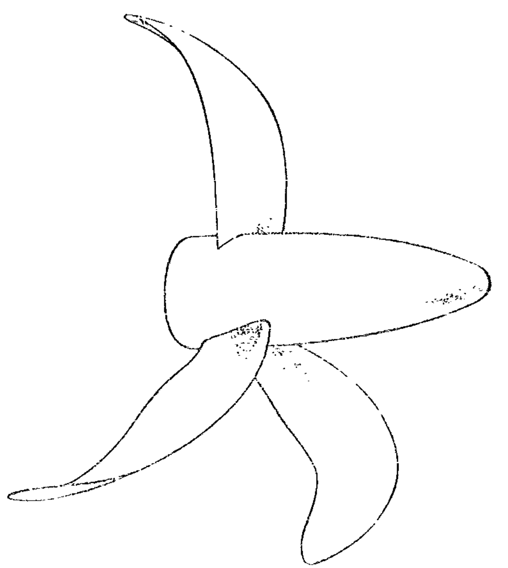


Figure 11 — German Engine and Propeller Developments

TABLE I

TURBOPROPELLER AND TURBOFAN DEVELOPMENT

NOTE: No detailed list of allied projects is presented since most of the active projects are Classified.

Item	*German Projects*	*Remarks*
Turboprop	BMW 028; Adaptation of BMW 018, 12,000 hp at 500 mph at sea level, wt 7700 lb. Design stage. Jumo 022; Adaptation of 012, 8000 hp at sea level. Preliminary design only. Daimler - Benz 021; Adaptation of Heinkel-Hirth Oll, 4000 hp at 500 mph at 25,000 ft. Design stage only.	U. S. leads Germany in having a low-powered turboprop in experimental operation, namely, the TG-100. Germany leads U. S. in development of high-powered unit, namely, the BMW 028. Recommend U. S. push development of larger powered units. U. S. needs greater capacity in compressor and turbine test facilities, and wind tunnels for testing large gas turbine nacelles.
High-Speed Propellers	Tests of swept-back propeller blades at DVL, Berlin, and AVA Göttingen, show improved efficiency at high-flight speeds.	Intensive investigation of swept-back propellers in high-speed wind tunnels recommended for U. S., since it shows possibility of increasing top speed of propeller-driven aircraft.
Turbofan	Design studies by Junkers, Heinkel, BMW.	Recommend immediate evaluation of this drive for application to U. S. aircraft.
Free-Piston Gas Generator	Junkers reciprocating free piston and LFA rotating free piston.	Rotating free piston shows promise of decreased weight and size over reciprocating free piston. Recommend German development be evaluated whether advantageous for applications in U. S.

	Germany	Britain	U.S.A.
1936	First Design Heinkel jet engine		
1937		First jet engine running	
1938	First run on Heinkel jet engine		
1939	First flight He 178	Contract for jet fighter by RAF	
1940	First run on Ju. 004 + BMW 003 jet engines		
1941		First flight "Squirt" ⇒ First airplane to U.S.A.	General Arnold directs development
1942	First flight of Me 262 with two Ju 004 engines	⇒ First engine to U.S.A.	First flight jet plane
1943			
1944	First use Me 262. start of large scale production	40 jet Ft per month, 20 Flying Ft. Models Experimental series	20 jet Ft per month Experimental series
1945			150 jet Ft per month

Data taken from German report dated 2 NOV, 1944

Figure 12

Figure 12 — Timetable of Turbojet Development

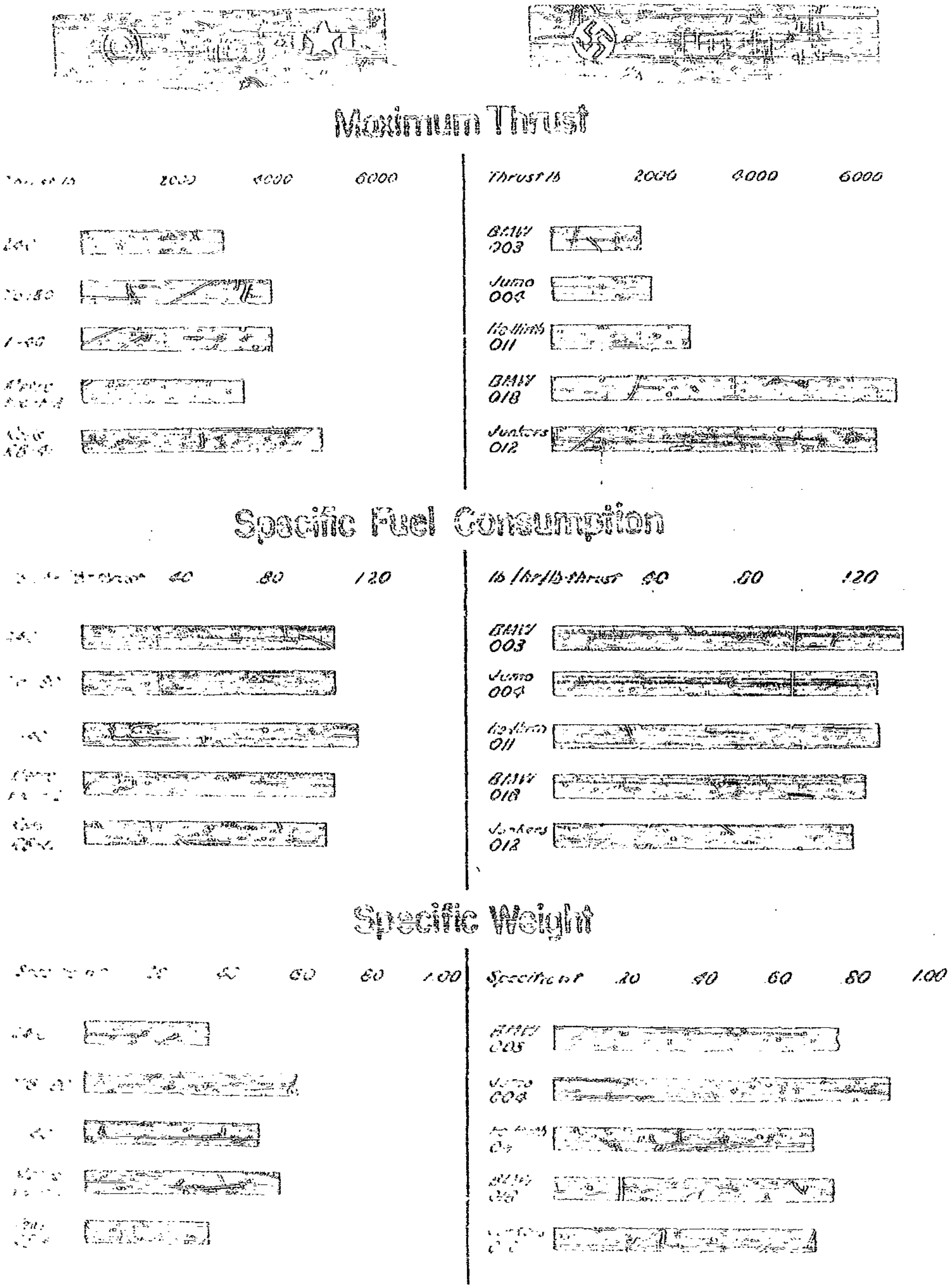


Figure 13 - Characteristics of Turbojets

TABLE II

GAS TURBINE PROPULSION RESEARCH PROBLEMS

Problem	*German Projects*	*Remarks, Outlook and Recommendations*
Higher Temperatures		
High Temp. Alloys	DVL and Industry	U. S. materials superior, but we should push research on fatigue improvement.
Ceramic Blades	LFA and AVA.	U. S. not behind, but research on improving brittleness needed.
Cooled Turbine Blades	Air-cooled; BMW et al. Water-cooled; Schmidt, LFA. Sodium-cooled; Rietz, AVA.	Evaluation of German water-cooled and sodium-cooled technique recommended.
Higher Take-Off Thrust		
Tail Pipe Burning	Used in Jumo 004.	Increased take-off thrust important for turbojets.
Liquid Injection	Experiments with H_20, HNO_3, N_2O.	Results promising but more thrust increase needed.
Overspeed at Take-off	Not much done.	German units handicapped by materials.
Variable-Area Nozzles	Most German jet engines have adjustable tail cones.	Development should also include adjustable stator vanes.
Aerodynamic Improvements		
Compressor Blading	Research at Göttingen, Stuttgart. Little research on increasing stage pressure rise by slots, flaps, and boundary layer suction. Extensive plans for test equipment at Braunschweig, Göttingen, 30,000-hp aerodynamic components laboratory planned at Ötztal.	Germany slightly ahead due to earlier start. Germany's 30,000-hp Ötztal components laboratory exceeds in scope all U. S. plans. Recommend a *full-scale* AAF components test laboratory to supplement basic research of NACA, which should also be expedited.

TABLE II — Continued

GAS TURBINE PROPULSION RESEARCH PROBLEMS — Continued

Problem	German Projects	Remarks, Outlook and Recommendations
Aerodynamic Improvements (Continued)		
Nacelle Aerodynamics	Wind-tunnel tests on jet-engine nacelles at Braunschweig, Stuttgart. Ötztal 100,000-hp, 27-ft diam, M = 1.0 wind tunnel for testing full-scale jet nacelles (80% complete).	Present German and U.S. wind tunnels inadequate in size and speed for jet nacelle tests. Germans had 100,000-hp tunnel under construction. Recommend large high-speed tunnel of similar size be included in plans for AAF equipment.
Cycle Improvement		
Intercooling and Reheat	Design studies by industry.	German emphasis on mass production of turbojets Postponed applied work on cycle improvement. U.S. work should be encouraged.
Regeneration	Design studies by industry; AVA ceramic heat exchanger	Recommend systematic research on efficient, light weight, heat exchangers.
Closed Cycle	No evidence of serious consideration.	Recommend Ackeret-Keller system at Escher Wyss, Zurich, be evaluated in terms of aircraft application, especially with use of helium.
Application to Missiles		
Subsonic Missiles	Design studies of expendable turbojets to replace Argus tube of V-1.	Recommend development of expendable, simply constructed turbojet for missile application.
Supersonic Missiles	No indication of German thought on supersonic turbojet application.	Recommend further studies of supersonic turbojet and construction of experimental model. Supersonic wind-tunnel facilities for testing propulsion units at supersonic speeds urgently needed.

turbojet as a propulsion unit for very high speeds, for example, speeds well beyond the velocity of sound.

Due to the importance of this subject, I initiated a Scientific Advisory Group Study of estimated turbojet performance at speeds extending beyond the speed of sound. The results showed that even with the present-day limitations of operating temperatures imposed by materials, the turbojet should outperform the ramjet up to a speed of 1.5 times the speed of sound, and that with increased temperatures still better performance would be obtained. This is in direct contradiction to a widespread belief existing at the present time that a compressor is useless for supersonic speeds, and that the simple ramjet becomes the logical propulsion system. Many other engineers seem to believe that neither the turbojet nor the ramjet is capable of functioning above the speed of sound, and that rocket propulsion is the only possible drive for supersonic flight. We do not believe that this is correct. Our analysis has definitely shown the feasibility of using turbojets for supersonic flying speeds. If the torbojet should be used for supersonic missiles, an expendable type turbojet must be designed in such a way that the manufacturing costs do not become prohibitive. The Scientific Advisory Group several times emphasized the importance of a study of expendable turbojet designs. German reports also include suggestions for the same type of development and at least one project was under way.

The divergence of opinions among various experts on this subject shows the necessity of further fundamental investigations which best can be done in supersonic wind tunnels.

It is our belief that the use of higher speeds will also affect the aerodynamic design of the turbines and compressors. The rotational speed of turbomachines is today often restricted by our lack of knowledge of supersonic flow patterns. The development of supersonic turbomachinery may lead to further reduction of the weight and frontal area of jet-propulsion units, and materially improve the performance of manned and unmanned airplanes.

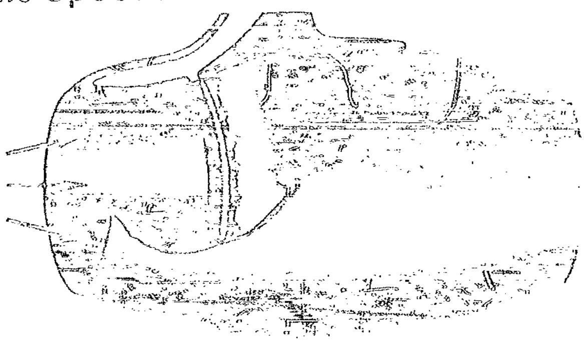
RAMJET

Ramjets and rockets are the simplest and lightest propulsive devices for aircraft and missiles. The fuel consumption of the ramjet is rather high and, therefore, in the whole field of jet propulsion, it occupies a place between the rocket and the turbojet. Unlike the turbojet, it does not use any mechanical compressor, the compression being obtained only by ram. Therefore, it is indeed a pure aerothermodynamic engine, without mechanical moving parts. Its maximum efficiency occurs naturally at very high flight speed. Hence, it is most suitable for propulsion of aircraft and missiles at transonic and supersonic speeds, especially for short flight durations. This is the reason why the idea of using ramjets, although it was suggested decades ago, lay undeveloped until today, the age of high-speed flight.

For maximum ram efficiency, the design of the entrance diffusers for transonic and for supersonic speeds is somewhat different as shown in Fig. 14.

Due to its promising future, the ramjet is being intensively developed by the Allies; it was earlier developed by the Germans. The situation is outlined in Table III.

For Transsonic Speeds



For Supersonic Speeds

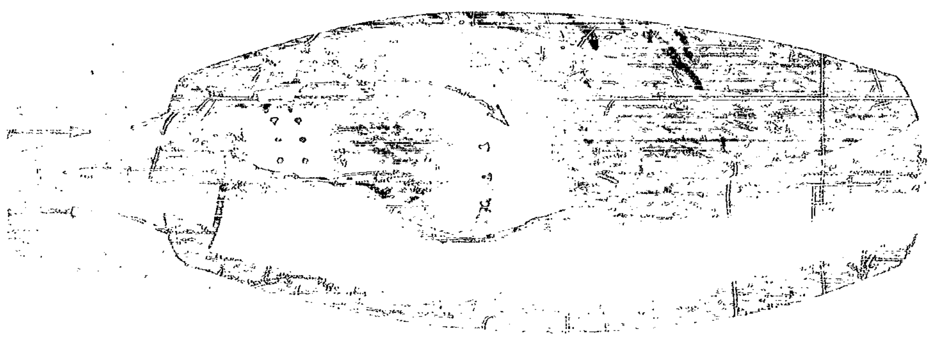


Figure 14 — Ramjets

TABLE III

RAMJET DEVELOPMENT

Germany	*Allies*
1943 Fa. Walter Co. of Kiel designed a ramjet which was tested at the LFA up to M = 0.85. Fuel consumption 7 lb/hr/lb of thrust.	1943 Combustion research was started at National Bur. of Standards and MIT.
1944 Focke-Wulf Co. designed a short ramjet which was tested at the LFA up to M = 0.90. The fuel was first vaporized before burning. Fuel consumption lower than Walter ramjet.	Further Allied development data classified CONFIDENTIAL
1944 W. Trommsdorf designed a ramjet projectile stabilized by spin. Few initial trials not successful.	
1944 E. Sanger and A. Lippisch suggested use of coal in ramjet as fuel. Combustion research done at Göttingen.	
1944 Supersonic diffuser for ramjet was studied both at Göttingen and LFA.	

A comparison of efforts shows that, although the Germans have run some wind-tunnel tests on their designs, we are not far behind in this initial phase of ramjet development. In fact, part of our effort is wisely directed toward the basic problem of combustion, thus insuring rapid future progress.

PULSOJET

The engine used for the German V-1 flying bombs was the first successful example of a pulsojet. The difference between the pulsojet and the ramjet is that the former utilizes the resonance effect of the duct to obtain higher combustion pressures; therefore, a better fuel economy is realized in the pulsojet than in the ramjet, which operates without resonance effect and depends on ram compression only. Also, due to this difference in operating principle, the pulsojet can produce a static thrust while the ramjet cannot. However, it is the general belief, substantiated by theoretical analysis, that the advantages of a pulsojet over a ramjet gradually disappear as the speed of flight increases. For supersonic speeds, the ramjet may be the lighter power plant, with the possible further advantage of smooth thrust. However, it seems to me that it is too early to say which power plant is the better one, and this decision should be postponed until more test data on both types of engine are available.

German development of the pulsojet was started by Paul Schmidt, the inventor, as early as 1935. As previously mentioned, its application to the flying bomb, V-1, must be considered as a temporary expedient, used only when the development of the V-2 rocket missile was delayed. The history of the pulsojet is shown schematically in Table IV. It is seen that, although the Germans were the first to have a working pulso-

TABLE IV

PULSOJET DEVELOPMENT

Germany		United States
1935	P. Schmidt started to develop the pulsojet under the auspices of GAF. Perfected an ignition device for 50 cyc/sec but found ignition unnecessary once engine was running. Complicated fuel injection.	U. S. projects still classified SECRET
1939	Argus Motor Co., Berlin, also started to work on the pulsojet. They had a cumbersome intake valve shaped like a spiral, but simple fuel injection.	
1940	The simple injection system of Argus was combined with the Schmidt spring air valve. Flight tests made.	
1941	Decision made to apply the Argus engine to V-1.	
1941 to 1944	Continued research to increase the thrust of V-1 engine, both by static and wind-tunnel tests. By removing part of the obstruction to the air flow, DFS Group has increased the thrust from 660 to 880 lb. A conical inlet for more air flow by P. Schmidt increased the static thrust to 1500 lb.	

jet, their more recent efforts have produced only limited success. The development program in the U. S., while started late, is more thorough and should yield reliable data for judging the comparative merits of the pulsojet and the ramjet in the near future.

ROCKETS

Rocket propulsion differs from the jet-propulsion devices hitherto mentioned in that the rocket does not utilize atmospheric oxygen. Its performance is, therefore, practically independent of altitude; in fact, the thrust produced increases somewhat when the outside pressure decreases. It functions best outside of the dense part of the atmosphere. As a matter of fact, it is the only propulsion device for the upper stratosphere and the stellar interspace.

Rocket propellants are either liquids or solid mixtures with moderate or slow rates of burning. Gaseous propellants require bulky containers and are, therefore, impractical. One class of the liquid propellants is called monopropellants; i.e., liquids which under action of igniters or catalyzers decompose and generate a large volume of hot gases. The expansion of the hot gas through the rocket nozzle accelerates the gas and generates the thrust. The bipropellants or the multipropellants are propellants consisting of two or more components. One component is the oxidizer which, when brought together with the other components in the rocket motor, sustains a vigorous combustion reaction and generates a large quantity of hot gas. The hot gas, in turn, produces the thrust by expansion through the nozzle. The combustion for some propellants has to be started by igniters or catalyzers. But there is a class of bipropellants, such as the combination of nitric acid and aniline, which is spontaneously inflammable when the components are brought into contact in the rocket motor.

One of the important findings of the study on rockets carried out by the Scientific Advisory Group is the fact that, barring the use of atomic energy, the optimum performance of all possible combinations of chemicals used as rocket propellants is not greatly different. Two methods of comparison can be used; comparison can be made on a constant weight-of-propellant basis or on a constant volume-of-propellant basis. The propellant which has the highest impulse per unit weight is the liquid oxygen and liquid hydrogen combination. But the propellant which has the highest impulse per unit volume is the nitric acid and aniline combination. The extremely low density of liquid hydrogen makes very large tanks necessary for its storage and, thus, practically rules out its use in the liquid oxygen and liquid hydrogen propellant. High impulse per unit volume (and, hence, small body and low drag) is very important in guided antiaircraft missiles which have to travel at high speeds in relatively dense atmosphere. The German choice of a nitric acid propellant for such missiles is believed to have been prompted by this advantage.

As a matter of interest, I shall include here the definitions of a few novel terms in German rocket engineering.

Monergol:	Monopropellant.
Hypergol:	Bipropellant or multipropellant that is spontaneously inflammable when the components are brought together in the motor.
Ergol:	The inert part of the fuel component in the "Hypergol." For instance, the aromatic gasoline in the mixture with aniline for nitric acid.
Initiator:	The active part of the fuel component of the "Hypergol." For instance, the aniline in the mixture with aromatic gasoline for nitric acid.
Katagol:	Monopropellant which is decomposed by catalyzer charged in the motor.

Liquid propellants are generally stored in tanks in the body of a missile and have to be forced into the rocket motor by one of the following methods:

1. Gas, under pressure, acting on the liquid surface in the propellant tanks. The gas can be obtained either from high-pressure storage tanks or from a gas generator, using part of the main propellant itself or a separate solid propellant for this purpose.

2. Liquid pumps. The pump has to be driven by a gas turbine using hot gas from a small combustion "pot" fed by a part of the main propellant supply or by an auxiliary propellant.

At present, the gas-fed systems are generally heavier than the pump-fed systems for durations longer than 30 sec and thrusts larger than 4000 lb. The gas generator system is, of course, lighter than the gas-under-pressure system due to the saving of the gas-bottle weight. On the other hand, the simplicity of the gas-fed system over the turbine-pump system has many advantages when really large-scale production for expendable weapons is considered.

Rockets as means of propulsion have been developed in the United States with two main applications in mind. The first application is the artillery rocket and the second application is the assisted take-off of heavily loaded airplanes from small airfields, and possible short-duration boost to achieve high performance. As actual operational experience was accumulated, it became evident that the requirement for large airfields, for landings by battle-weary pilots, and the power boost of conventional engines by water injection, practically eliminated the necessity for asissted take-off as far as land based bombers are concerned. However, some recent developments indicate a renewed interest in rockets. These developments are:

1. Long-range winged missiles, rising to extreme heights where the rocket is the only power plant which can operate without the assistance of atmospheric oxygen.

2. Guided antiaircraft missiles with a rocket as the main propulsive unit or as the launching device.

3. Launching of supersonic, long-range, pilotless or manned airplanes.

The task of the rocket in launching and take-off of supersonic airplanes and winged missiles is not fully covered by the term assisted take-off. In fact, the rocket will in many cases be the main source of power for take-off of such aircraft.

Both in the U. S. and in Germany, after rocket engineers had succeeded in constructing liquid-fuel rocket motors of several minutes endurance, the idea came up to use rockets as sole power plants on manned airplanes capable of short duration flights. In Germany, such an airplane (the Me-163B) actually was used in combat as an interceptor. However, it is doubtful whether such an airplane will be justified after power plants of almost similar lightweight as the rocket motor but with much lower fuel consumption, like the ramjet, become available, and after perfected target-seeking missiles have taken over the task of short duration manned interceptors.

The historical development of rockets by the Germans is summarized in Table V. It is seen that the Germans were forced by the requirements of the war to develop cheap and easily manufactured propellants and to accept the difficulties of handling such propellants as nitric acid and hydrogen peroxide.

There is no doubt that the various applications for rocket motors mentioned above fully justify the statement that rocket research and development have become one of the most important responsibilities of the Air Forces for the future. It is true, of course, that many applications of the rocket concern the ground and naval forces. However, the Air Forces should maintain leadership in rocket development as a main and an auxiliary source of power for manned and pilotless aircraft; they should develop their own facilities for testing rocket propulsion devices; and they should secure a free hand in maintaining the collaboration of the best scientific personnel and the best equipped laboratories in the Nation. Our early perfection of long-duration solid-propellant rockets, and the promising results obtained with nitric-acid aniline and nitromethane liquid propellants should be further exploited. The propulsion of long-range winged missiles and antiaircraft missiles, and the take-off of supersonic aircraft are important Air Forces applications which call for powerful progress in rocket engineering.

TABLE V

DEVELOPMENT OF ROCKETS

Germany	United States
1. The German solid propellant for artillery rockets has a wide operating temperature range of from $-40°$ to 140°F.	U. S. projects still classified SECRET
2. To obtain smooth burning at pressures below the critical pressure of the solid propellant, a spring-loaded regulator valve is fitted to the motor.	
3. The handling of 80% concentration of H_2O_2 was made relatively safe. Long duration H_2O_2 and methyl alcohol and hydrozine hydrate rocket was perfected for Me-163B. Turbine-pump system functioned well.	
4. The difficulty of producing enough H_2O_2 and the advantage of high density of nitric acid-aniline propellant for guided missile application forces the Germans to use the latter. Improvements are made to shorten ignition lag, even after the addition of inert component to the fuel.	
5. Film cooling and evaporative cooling was developed, particularly for high performance propellants such as liquid oxygen and alcohol.	
6. Early trial on monopropellant not successful. The Schmidding propellant, a mixture of methyl nitrate and methyl alcohol, was not reliable.	

ATOMIC ENERGY FOR JET PROPULSION

Based upon the published values of the measured heat of fission of U^{235}, it is calculated that the available energy of this material is 3.120×10^{10} BTU per pound. This is more than 1,500,000 times the lower heat value of gasoline, the most powerful fuel generally used today. The study of chemicals suitable for fuels or rocket propellants indicates that no really radical improvements in the BTU per pound ratio can be expected within the frontiers of molecular reaction. It will be possible to produce fuels and propellants more suitable for certain types of engines, increase their safety, improve their handling quality, and lower their costs of production. Nevertheless, no hope for spectacular improvements in range and speed performance of aircraft can be derived from further development of conventional fuels. Use of atomic energy as fuel, however, will radically change this situation.

The question of whether or not and how atomic power can be produced continuously and at a constant rate suitable for propulsion cannot be discussed in this report. Let us transfer our thoughts to an era in which the fundamental aspect of the problem already has been solved.

It appears to me that the application of atomic energy to transportation will probably precede the application to power generation for stationary purposes. In the latter case the cost is the governing factor; in transportation, it is the cost and the weight of the fuel to be carried. In high-speed aerial transportation the importance of weight transcends the importance of cost. Hence, it may be concluded that the extremely expensive atomic agent, now having been developed as an explosive, will be used for propulsion and probably jet propulsion.

In speculating on the possible use of atomic energy for this purpose we have to change our usual concepts. For example, the weight of the fuel proper is certainly negligible. In other words, the available energy is almost unlimited. The problem is how much of this energy we shall be able to utilize in an engine of limited size and limited weight, where the weight of the engine includes all materials which have to be carried in the vehicle besides the atomic fuel proper.

Let us consider, for example, the case of rockets. We shall exclude the use of the disintegration products as working fluid for the rocket. The temperature of the disintegration products alone without dilution would be too high for any known or possible engineering materials to resist. Since temperature is the limit, the most efficient expansion process for the fluid is the isothermal expansion, with the temperature of the gas kept at the maximum allowable value by constant reheating. Inasmuch as one obtains the highest exhaust velocity by using a working fluid with the least possible molecular weight, hydrogen should be used. Then assuming a maximum temperature of 8000°F, which would require cooling, of course, and a chamber pressure of 100 times atmospheric pressure, we can obtain a specific impulse of 1365 lb-sec/lb of hydrogen carried in the vehicle. This means that the specific propellant consumption of rockets would be reduced from the present day value of 18 lb/hr/lb of thrust to 2.6 lb/hr/lb of thrust. This is a great reduction, even though the ratio is far below the spectacular figures for the ratio of the effectiveness of atomic and conventional bombs. However, the use of atomic energy would certainly allow the construction of rocket-driven pilotless aircraft which could reach any point of the globe without stop. Even interstellar navigation appears feasible.

As to jet-propulsion devices using atomic energy with atmospheric air as working fluid, the fuel consumption itself again would be negligible. The size and performance of the craft driven by atomic power would depend mainly on the weight of the auxiliary materials like moderators, and devices for cooling and for controlling the rate of energy production. Of course it is difficult today to make any estimate of the bulk and weight of such equipment.

The most interesting feature of such a propulsion system is that the overwhelming part of the weight to be carried by the vehicle is independent of the endurance and only a very small portion of the weight is proportional to the flying time or the range desired. In other words, if one succeeds in reducing the engine weight to the limiting value which makes flight at a certain speed possible, very small further reduction of the weight would increase the range almost without limit.

It seems to me that there are possibilities in the development of nuclear energy for jet propulsion which deserve immediate attention of the Air Forces. To be sure there are problems still to be solved requiring inventive activity of specialists in nuclear physics. However, the main problems are engineering problems requiring inventive genius of the same order but different kind. We have to convert the energy liberated by the nuclear reaction into heat of such temperatures as needed for our propulsive devices. Important problems to be solved are in the nature of heat transfer, resistance of materials to heat, corrosion, etc. It appears necessary to find a way, within the limits of necessary security, for engineering talent which could be used to accelerate the progress in the field of propulsion. It would secure us the conquest of the air over the entire globe without range limitations.

It is my feeling that the Air Forces should, as soon as possible, take the lead in investigating the possibilities of using nuclear energy for jet propulsion.

JET PROPELLED AIRCRAFT

Of the novel power plants mentioned in this report, only the turbojet and the liquid-fuel rocket motor have been successfully used on aircraft.

Our Bell P-59 (turbojet), Lockheed P-80 (turbojet), and Ryan FR-1 (reciprocating engine and propeller plus turbojet) are all well known to the Commanding General.

The Germans had developed and used some jet-propelled aircraft in combat, and had others under development. This is shown in Table VI.

For future fundamental planning, a very careful choice of propulsion systems is necessary. It is possible to make a basic analysis, computing for various systems the sum of the specific weight of power plant and fuel required to travel at a given speed for a certain endurance. Then the optimum power plant is the one for which this sum has a minimum value. However, it is impossible to decide rigidly from such a simple study which type of propulsive system is best for a certain purpose. Beside the minimum specific weight of the power plant and fuel, many other aspects enter the picture. One important factor is the frontal area of the engine. Then also the structural weight of the airplane is influenced by the choice of power plant. The jet-propelled airplane has the advantages of not requiring a minimum ground clearance for the propeller, and of being comparatively easy to maintain. On the other hand, jet propulsion introduces aerodynamically difficult problems such as the intake and ducting of very large quantities of air.

No one has doubts about the great future of jet propulsion in military aircraft. However, such general statements as "one or two years from now all fighters and bombers will be jet propelled" should be replaced by careful, scientific analysis which secures jet propulsion its proper place, but does not exclude other combinations such as the turboprop or, in the case of extreme ranges, the reciprocating engine and propeller. The choice of the most efficient power plant must not be influenced by any general feeling that the propeller appears obsolete.

I believe that German high-speed wind-tunnel results will prove to be very helpful in our designs in connection with aerodynamic and vibration problems originating from interference between the jet system and the air frame. However, the Air Forces should, in cooperation with aircraft designers, initiate a comprehensive high-speed wind-tunnel test program in order to obtain further information in this field. The ATSC took the first step in such a program by holding a meeting between NACA, industry, the Navy and the ATSC in late summer, 1945. However, any program which is undertaken will be severely restricted and handicapped for a long time by the lack of high-speed wind tunnels of sufficiently large size.

The two rocket airplanes mentioned in Table VI, the Me-163B and the Natter, are of special interest because pure rocket motors were their sole source of power. The

Table VI
CHARACTERISTICS OF GERMAN JET AIRPLANES

AIRPLANE	HE-162	ME-262	ARADO-234	ME-163 B	HORTON-229	JU-287	BP-20 'NATTER'
USE	FIGHTER	FIGHTER	BOMBER	TAILLESS FIGHTER	FLYING WING FIGHTER	BOMBER	FIGHTER
ENGINE-NAME & TYPE	BMW-003 E-1 OR E-2	JUMO T-J UNITS TL 109.004 B-1	JUMO-004	BI-FUEL ROCKET MOTOR HWK 509 A-1	JUMO-004	JUMO-004	BI-FUEL ROCKET MOTOR HWK 509 A-2
NUMBER OF ENGINES	ONE	TWO	TWO	ONE	TWO	FOUR	ONE
MAXIMUM THRUST	1,760 LB @ S.L. STATIC	4,000 LB @ S.L. STATIC	3,900 LB @ S.L. STATIC	3,650 LB S.L. STATIC		8,000 LB @ S.L. STATIC	3,750 LB
GROSS WEIGHT	5,940 LB	11000 LB	20,900 LB NORMAL LOAD	11,500 LB NORMAL LOAD		50,600 LB	4920 LB
WING LOADING	49.5 LB /SQ FT	40.7 LB /SQ FT	72 LB /SQ FT			81.6 LB /SQ FT	95.5 LB /SQ FT @ TAKE-OFF
MAXIMUM SPEED	522 MPH @ 19,700 FT	550 MPH @ 30,000 FT	500 MPH	590 MPH - @ 25,000 FT	550 MPH @ 20,000-25,000 FT	485 MPH @ 16,400 FT (55400 LB MEAN WT)	620 MPH @ 16,400 FT.
MAX. RANGE OR ENDURANCE	620 MI @ 36,000 FT 65 MIN @ 36,000 FT	945 MI @ 30,000 FT 90 MIN	600 MI-WITH 1100 LB BOMBS 900 MI — NO BOMBS	10-12 MIN FULL POWER	1 HR @ 22 500 FT		36 MI AFTER CLIMB 4.56 MIN-500 MPH-9800 FT
TAKE-OFF DISTANCE	2625 FT-NO ASSIST 1245 FT-WITH ASSIST	3300 FT HARD SURFACE 5000 FT TURF	4200-4500 FT	3,600 FT ±			VERTICAL
RATE OF CLIMB	4,250 FT/MIN @ S.L.	4,600 FT/MIN. @ S.L		10,000 FT ±/MIN @ 40,000 FT ALT			37400 FT/MIN @ S.L
LANDING SPEED	102 MPH	112-124 MPH	APPROX. 110 MPH		81 MPH		
STATUS	FLYING EXPERIMENTAL	IN COMBAT	FIGHTER VERSION IN COMBAT	IN COMBAT	DESIGNED	DESIGN STAGE	FLYING EXPERIMENTAL

Table VI — Characteristics of German Jet Airplanes

Me-163B was more or less conventional, in that take-off and climb were accomplished under its own power. However, the Natter was intended to be launched nearly vertically by means of two or four solid-propellant launching rockets. It was to be aimed at a point 2 km behind the point of collision so that attack on a bomber could be made from the rear. This rocket-propelled interceptor was armed with 24 rockets of 7.3-cm caliber. After the rocket ammunition is exhausted, the airplane is caused to disintegrate; the nose section is allowed to fall freely and be expended but the air frame with rocket propulsion motor and the pilot are saved by parachutes. A former Luftwaffe pilot, who had been convicted of some crime, acted as test pilot in the first flight of the Natter and was killed.

Rocket airplanes have, at the present time, intrinsically, only a few minutes of endurance. Their use as interceptors in the future may be made unnecessary by the development of more economical propulsive devices of light weight, and perfection of target-seeking electronic or heat devices which would eliminate the need for a pilot. However, I highly recommend that the rocket-type of airplane be developed at the present time for research purposes. One advantage of rocket drive in this case is the possibility of exact thrust measurement, which is extremely difficult for any other propulsive system. These research airplanes would be very useful for studying performance, flow conditions, and flight mechanics.

TAILLESS AIRCRAFT

In Germany, tailless aircraft were intensively developed by A. Lippisch and by the Horten brothers. The Junkers' designers did a considerable amount of engineering study on large tailless airplanes but none were actually constructed.

Lippisch worked on the design of tailless airplanes at DFS beginning in 1936. He designed a series of about eight aircraft, before the time when he came in contact with Messerschmitt and developed the Me-163A and Me-163B. Stability problems were encountered at high speeds and the Me-163B was "redlined" at a Mach number of 0.80 (590 mph at 25,000 ft). Satisfactory stalling characteristics were obtained by a special low-drag fixed slot at the wing tips. A vertical tail was found necessary for satisfactory directional stability. Lippisch's latest design was the P-11, a tailless aircraft with two turbojet engines. The critical Mach number was estimated to be 0.92 (about 680 mph at 25,000 ft); wind-tunnel tests indicated a drag coefficient as low as 0.0063.

The Horten brothers flew their first tailless aircraft in 1935. They received no support from the Air Ministry until February, 1945, following the publication of a photograph of a Northrop tailless airplane in "Interavia." Their design was to be powered with two Jumo 004 turbojet engines. Computed high speed was about 600 mph.

The development program for tailless aircraft has been more extensive in the United States than any place abroad.

The Northrop XP-56 was a pusher-type, flying-wing fighter. This airplane was flown only a few times and indications were, from these tests, that the performance was short of expectations and that difficulties in control were encountered. Unfortunately, wind-tunnel tests necessary to trace the basic reasons for these difficulties could not be carried out, because no high priority could be attached to merely experimental projects.

Theoretical studies here and abroad show significant advantages (for example, longer ranges) for tailless aircraft over tailed aircraft, especially in the case of gross weights of 150,000 lb and more. Of course it must be assumed that the tailless aircraft is made stable and maneuverable without measures which would compromise the performance. The recent recognition of the advantage of swept-back wings for very high speeds makes the tailless airplane particularly attractive also for transonic airplanes. It is the opinion of the Scientific Advisory Group that the development of tailless aircraft should be encouraged; however, actual construction should be supplemented by extensive wind-tunnel investigations of methods for improving stability and control at high speeds.

AERODYNAMIC MISCELLANEA

By aerodynamic miscellanea, I mean auxiliary items which contribute to the advance of the aerodynamic art. The items which I now consider are:

1. Flow Measurement Techniques,
2. Laminar Flow Wings, and
3. Boundary Layer Control.

A discussion of these miscellanea follows, with a brief review of German developments and comparison with our own.

FLOW MEASUREMENT TECHNIQUES

The average level of German development in wind-tunnel instrumentation appeared somewhat below our own, although in some instances they had surpassed us, especially in fields such as supersonic aerodynamics where their basic facilities were more advanced. On the other hand, their electronic equipment was generally inferior to ours.

In high-speed air flow, in both the transonic and supersonic range, instruments which project into the air stream cause excessive disturbance of the flow. For this reason, both German and Allied areodynamic instrument development work was concentrated largely on methods of studying air flow by methods which do not disturb the flow pattern.

Several interesting German developments were:

1. Combination Schlieren and interference methods which show both density gradients and lines of constant density on the same observation screen or photographic plate, as shown in Fig. 15.

2. A novel X-ray method of measuring density, which makes use of the fact that the absorption of an X-ray beam is dependent on the density of the medium through which it passes.

3. A corona method of measuring velocity, which utilizes the fact that the potential of a corona discharge varies with the speed of the air passing by.

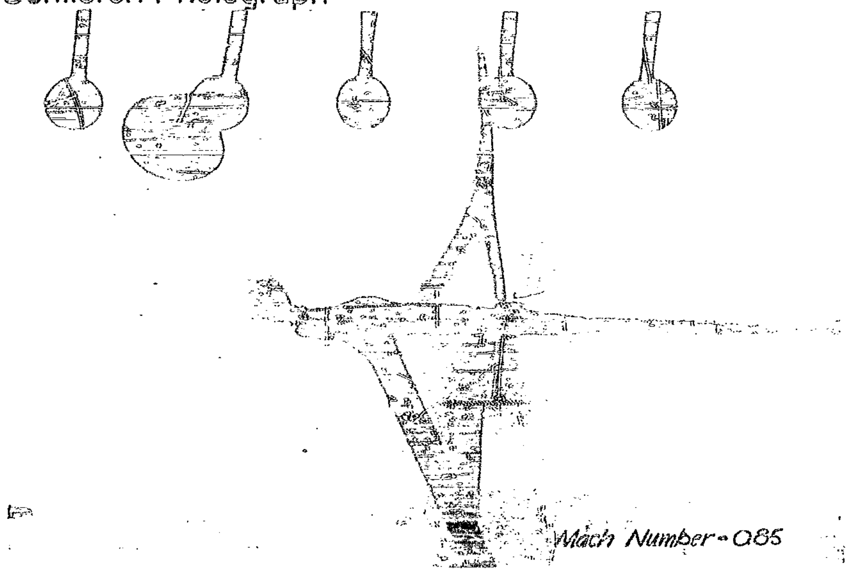
4. A spark method of determining local temperature, by measuring the local speed of sound, at which the disturbance, caused by a spark discharge, travels.

A brief comparison of German and Allied developments in measurement technique is given in Table VII.

LAMINAR FLOW WINGS

In this field we were far ahead of the Germans. In the following paragraphs, the German development status will first be given, followed by our own.

Schlieren Photograph



Interferometer Photograph

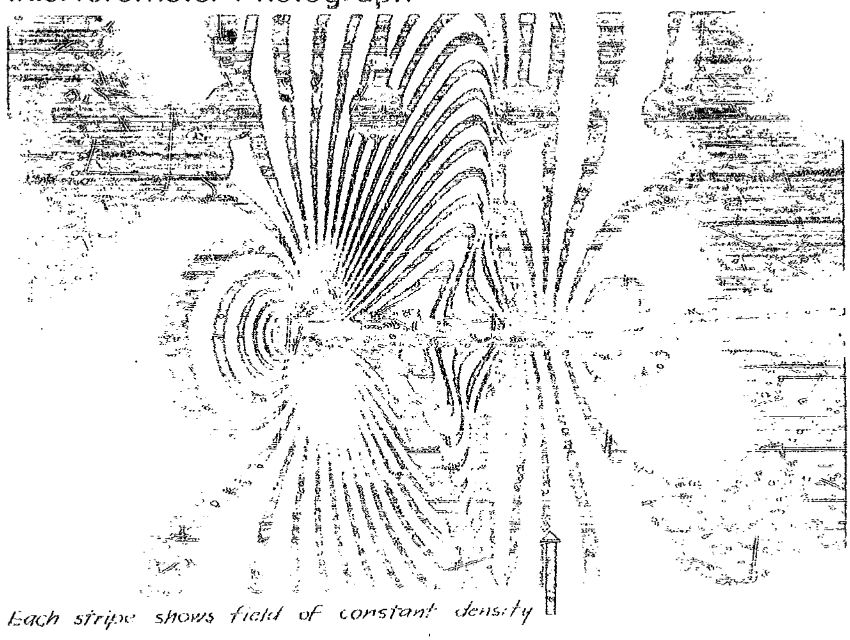


Figure 15 — High-Speed Airflow Photographs

TABLE VII

FLOW MEASUREMENT TECHNIQUES

Item	*German Development*	*Allied Development*
Interfero-meter	Extensive development at LFA, AVA, WVA for measuring density in high-speed air flow; nothing new in principle but considerable development of details. LFA has system whereby simultaneous Schlieren and interference pictures are recorded on the same photographic plate.	U. S. development by Ladenburg, Princeton. Also small project by Dr. Williams, Pasadena. U. S. application lagging German.
X-Ray Method	This method used at Kochel utilizes principle that absorption of X-ray beam is a function of density of the medium through which it passes. Ionization meter is calibrated in terms of density.	Unknown to Allies.
Schlieren Method	All supersonic wind tunnels have associated Schlieren equipment. Largest mirrors are 1.2 m in diam, under construction for Kochel 1 m by 1 m Mach number 7.0 tunnel.	Used in the few existing Allied supersonic wind tunnels.
Spark Method	A spark creates a disturbance travelling at the speed of sound. Measurement of the local speed of sound determines the local temperature. Developed for WVA.	Application to temperature determination unknown to Allies.
Ultrasonic Waves	Generation of high-frequency waves affords another method of determining temperature by means of measuring the local velocity of sound.	Application to temperature determination unknown to Allies.
Hot Wire	Some work at Gottingen but not very advanced.	U.S. developments, especially by Dryden, Bur. of Standards; also by Liepmann, CIT; superior to Germans. British work also more advanced than Germans.
Corona	Aachen development of corona for velocity measurement.	Experimental development by Lindvall, CIT, in 1935. Not continued. Some work at MIT.
Doppler Method	Method developed at Fassberg for measuring speed in the jet of rocket, by means of the Doppler effect.	This method not used by Allies for measuring speed of rocket discharge.
Electro-Magnetic Balances	Used in many of the intermittent wind tunnels, such as LFA, AVA, WVA, to measure transient forces.	In common use in U. S. wind tunnels. Electronic technique in general superior to German.

TABLE VII — Continued

FLOW MEASUREMENT TECHNIQUES — Continued

Item	*German Development*	*Allied Development*
Piezo Elec. Capsules	Used at LFA for measuring transient forces.	This method is also in use by Allies for special purposes.
Half Models	This technique used at WVA; convenient for measuring pressures, hinge moments, etc.	This technique also used at CIT.
Cavitation	Similarity between cavitation and compressibility phenomena used for qualitative work in water channels on simulated critical compressibility conditions.	Water channels not used by Allies for simulated compressibility effects.
Simulated Turbojets	For wind-tunnel models, small high-speed compressors are used to simulate internal flow, and alcohol is burned to introduce heat.	Not used as yet by Allies for wind-tunnel models of jet aircraft.
Flexible Walls	In some supersonic wind tunnels, continuous flexible walls of the test section are used to change Mach number. Some tunnels used fixed nozzles and variable diffuser.	Flexible walls have been ordered for Aberdeen, Wright Field, and Ames supersonic wind tunnels. Flexible walls have been in use for several years by NACA and in England.
Half-Open Jets	In some supersonic tunnels the test section is partly closed and partly open. This is said to decrease wall interference, especially through transonic range.	This technique not as yet used by the the Allies for supersonic flow.

German Developments.

According to the German aerodynamicist Schlichting, German work on laminar flow airfoils did not start until about the end of 1938. By 1940, Schlichting considered that the fundamentals were known. Drag coefficients as low as 0.0027 were reached at a Reynolds Number of 5×10^6, but the German scientists were unable to retain the low drag at higher Reynolds Numbers. They were handicapped by lack of suitable low-turbulence wind tunnels. On one occasion, Prandtl reported: "Suitable wind tunnels for the conduct of airfoil investigations at sufficiently high Reynolds Number and at low turbulence are lacking in Germany. On the other hand, it is known that in the U. S. A. particular installations created for this purpose are working exceptionally vigorously in this field."

Tests were made on a Japanese laminar flow airfoil, on three airfoils derived from one member of an obsolete NACA Series 27215 (which was described in a captured French secret report), and on a few airfoils designed by Schlichting. The Germans also had some information on a Russian laminar flow airfoil obtained from a captured report.

The Germans never used laminar flow airfoils on aircraft. They were astonished and mystified by the performance of the Mustang and made many wind-tunnel and flight tests. They gave the following tabulation of wing profile drag coefficients (obtained by momentum method) for a number of airplanes at lift coefficient of 0.2:

He-177	0.0109	Ju-288	0.0102
Me-109B	0.0101	FW-190	0.0089
Mustang	0.0072		

The German comment is: "The drag of this only foreign original airfoil tested up till now is far below the drag of all German wings tested in which it should be remembered that it was tested without any smoothing layer."

Another writer says: "A comparison of flight measurements shows quite unmistakably that the Mustang is far superior aerodynamically to all other airplanes and that it maintains this superiority in spite of its considerably greater wing area."

Allied Developments.

The NACA began investigations of laminar flow airfoils in a low-turbulence wind tunnel in the spring of 1938, and the encouraging nature of the results obtained (without details) were described in the Wilbur Wright Lecture of the Royal Aeronautical Society on 25 May 1939, and in the NACA Annual Report for 1939. In June, 1939, an advance confidential report by Jacobs was released. A summary was published in March, 1942 in confidential form. The most recent summary was relaesed in March, 1945, and this summary has been kept up to date by supplementary sheets.

As indicated in the summary of German developments, the Allies are far ahead in low-turbulence wind-tunnel equipment and in knowledge of laminar flow airfoils and their application to aircraft. Drag coefficients as low as 0.003 at a Reynolds Number of 20 x 10^6 have been obtained.

A summary of the present state of knowledge is given in the NACA restricted report L5C05, "Summary of Airfoil Data," by Abbott, von Doenhoff, and Stivers, March, 1945.

BOUNDARY LAYER CONTROL

In this field the Germans had an advanced start and had just about reached a practical state. A discussion of German and Allied developments follows.

German Developments. Considerable work was done on boundary layer control at AVA, Göttingen, starting in 1925. The first airplane with boundary layer control was built and flown in 1932.

From about 1942 on, work was intensified. Schwier obtained a maximum lift coefficient of 4.5. using pressure jet boundary layer control in wind-tunnel tests. In July, 1943, Stüper obtained a maximum lift coefficient of 3.8 in full-scale flight tests with boundary layer control by suction. The maximum lift coefficient on his airplane without boundary layer control was 1.9. About the same time, a maximum lift coefficient of 3.4 with boundary layer control was reported in wind-tunnel tests of a four-motored airplane which was to be developed by Junkers. A unique suction and pressure-jet boundary layer control system was used. Air was sucked in over the inboard portion of the wing, just ahead of the flaps, and blown out over the outboard portion of the wing, just ahead of the ailerons. In November, 1943, Wagner outlined work which was done at Arado, showing a maximum lift coefficient of 4.0 to be possible.

All German investigators noted that the internal wing ducting required and the power required to drive the boundary layer control equipment constituted serious obstacles to the successful, practical application of boundary layer control. However, it was felt that these obstacles could be successfully met. At the end of the war, an Arado transport airplane, having low landing and take-off speeds because of boundary layer control, was in service in the German Air Force.

United States Developments.

An L-1 airplane was equipped with boundary layer control by suction. The maximum lift coefficient was 3.5 without boundary layer control and 3.6 with boundary layer control. The landing speed of the modified L-1 was considerably higher than that of the original airplane due to the weight of the boundary layer control equipment.

Boundary layer control has an important application in making low landing speeds possible on high-speed aircraft. It also appears that the potentialities of boundary layer control in the transonic speed range have never been systematically evaluated. We found that some interesting work was done by Ackeret at the Institute of Technology in Zurich, Switzerland. The Scientific Advisory Group recommends that an intensive research program on boundary layer control be under taken by the Army Air Forces.

THE ART OF RADAR

INTRODUCTION

The last four years of war-stimulated research have resulted in the development of equipment and techniques in the radar and electronics field which offer possibilities of profoundly affecting the whole concept of future air force operations. These devices have already passed the laboratory stage, and nearly $3,000,000,000 worth of radar equipment is now in actual combat use in the Army, the Navy, and the Air Forces. Thus, the fundamental ideas in the field have been thoroughly proven and are definitely here to stay.

In spite of the rapid progress made in a relatively short time, the technique in this field is still in its infancy. Enormous possibilities lie ahead, and additional research, both on the technical and on the operational side, will pay huge dividends in more effective air force operations.

At the same time, the rapid introduction of new and miraculous devices has led to the feeling among the uninitiated that anything is possible by the use of electronics. It is, therefore, of greatest importance to understand thoroughly the limitations as well as the possibilities of radio, radar, and electronic equipments in order to avoid raising impossible hopes and in order to eliminate unnecessary and ill-conceived research and development programs.

Fundamentally, radar is a device which enormously extends the range, power, capabilities, and accuracy of human vision. For example:

1. The human eye cannot see in darkness or through fog, clouds, and rain. Radar is not at all limited by darkness or by fog, and to only a slight extent by heavy clouds and rain.

2. The human eye determines only roughly and with difficulty the distance to an object which it sees. Radar determines the distance rapidly, accurately, and continuously.

3. The human eye can pick up or see objects such as airplanes only at distances of a few miles. Suitable radar can see airplanes at distances up to 200 miles.

4. The human eye, aided by optical instruments, can get accurate data on bearing, elevation, and range of only one distant object at a time, and considerable time is required for such determinations. Radar can determine and display these data within a few seconds for all objects in view over an enormous area, in the best cases up to a radius of 200 miles.

These features of radar open up many possibilities, such as: all-weather day and night air operations; an increase in accuracy and versatility of bombing, gunfire, and navigation; the control from the ground or from the air of major air force operations;

provision of information and controls to relieve the overburdened pilot, both in navigation and in combat; and, the accurate remote control of pilotless aircraft.

Furthermore, it must be realized that radar is not a facility or attachment which will occasionally be used under bad conditions. Rather, the air force of the future will be operated so that radar is the primary facility, and visual methods will be only occasionally used. Bad weather or darkness are normally prevalent from 60 to 90% of the time, and predictions of good weather at remote points fail to be realized from about 25 to 50% of the time. Hence, in an all-weather air force, radar must be the universally used tool for bombing, gunfire, navigation, landing, and control. The whole structure of the air force, the planning of its operations, its training program, and its organization must be based on this premise. The development and perfection of radar and the techniques for using it effectively are as important as the development of the jet-propelled plane.

GERMAN RADAR DEVELOPMENTS

Broadly speaking, the radar art in Germany at the end of the war was in about the same state as it was in this country and England in early 1942. The Germans did not realize the possibilities of microwave radar, for example, until they inspected equipment shot down in British and American airplanes. Furthermore, they were forced, during the latter years of the war, to concentrate their efforts on defensive measures and, hence, never developed a concept of the offensive use of radar. Finally, the British and American jamming and countermeasures techniques were so effective that over half of the German radar development talent was forced into the task of developing antijamming measures, to protect their own existing radar equipment. This did much to stop progress in the development of new radar techniques.

The beginnings of German radar took place at as early a date (1936) as the corresponding developments in the United States and England. By the beginning of the war the Germans had an early warning system of good design and were making progress on equipment for control of fighter aircraft and for antiaircraft artillery. The German scientists felt that 50 cm was about the shortest wavelength that could be practically employed in radar and concentrated very considerable engineering talent on the development of a variety of equipments at this wavelength. Their engineers considered the development of microwave techniques, but discarded this possibility as impractical because no adequate transmitter at such frequencies was known to them. The equipment they had in use at 50 to 60-cm wavelengths, however, was excellent in its engineering design and very large quantities were in actual use.

Germany suffered seriously through the lack of a good organization of their radar and electronics development effort. Most of the development took place in industrial laboratories such as those of Telefunken, but the very brilliant group of German physicists in universities were never called in to participate. Consequently, while engineering design was good, imaginative new thinking was lacking. The industrial engineers complained that they received no intelligent and understanding cooperation from any of the military agencies. They believed that the top military commands had no conception of the importance of radar and electronic equipment. On the other hand, the university scientists did not take the initiative to mobilize their efforts themselves as was done in the United States and England. The close coordination which existed in this country between both technical and operational military officers, the industrial laboratories, and the university scientists was completely lacking in Germany. Some attempt to remedy this situation was made in late 1944, but the effort never got going before the end of the war. The development work was scattered widely throughout the country, largely due to the disruptive effects of Allied bombing, and the various agencies and laboratories worked independently and without adequate coordination.

The only German radar put into extensive tactical use was that designed for air warning and air defense. Early warning stations, ground-controlled interception stations, antiaircraft fire control equipment, and airborne aircraft interception equipment were all in effective use. The techniques used by the Germans for navigational assistance to bombers on offensive missions during the Battle of Britain did not utilize radar, but employed elaborations of the United States airway navigational aids. Ingenious radio beam techniques were employed and in some cases these were made to operate bomb computing devices in the aircraft. However, the British jamming of these radio beams was very effective, in spite of strenuous efforts continuously made by the Germans to change frequencies and otherwise alter their techniques to avoid jamming. The concept of using microwave airborne radar for bombing and attack on shipping apparently did not come until British and American planes carrying such equipment were shot down over German-occupied territory. The capture of this equipment created a considerable sensation among German scientists and military experts. A large effort was immediately undertaken to copy this equipment. However, no sooner had a start been made on copying 10-cm equipment than 3-cm equipment appeared in American planes. Rumors that even shorter wavelengths were being developed by the Allies caused the Germans to start work on 1-cm and shorter wavelength devices. Their efforts became so scattered thereby that apparently no micro[illegible] equipment at all was ever put into production. In addition, the efforts of the engine[illegible]s were also diverted to improving their air-defense equipment and to f[illegible]g me[illegible]ds of avoiding Allied countermeasures, so that the positive efforts to dev[illegible] radar [illegible] new offensive uses were greatly retarded. The concept of using rad[illegible] for th[illegible] ground control of tactical and strategic air operations, so successfully employed [illegible] the U. S. 8th and 9th Air Forces, apparently never occurred to the Germans, [illegible]en though some of their ground equipment could have been adapted [illegible] this pur[illegible]ose.

The development of rockets and oth[illegible] unman[illegible]d missiles was far more actively pursued in Germany than the devel[illegible]ent o[illegible]ectronic equipment. As a result, apparently no advanced electronic or [illegible]dio [illegible] [illegible]rol methods for their missiles comparable with Allied developments ev[illegible] [illegible]nd the paper or laboratory stage. Had the Germans had an active coordin[illegible] [illegible]onic development program comparable to that built up by the Allies and h[illegible] this [illegible] combined with their missile work, some dangerous weapons might have [illegible]sult- [illegible] [illegible]arious ideas were reported by individual workers for the control of [illegible] [illegible] aerodynamics laboratories apparently did not have adequate electronic [illegible] electronic engineers were largely cut off from contact with the aerod[illegible] [illegible]bly the most successful missile development organization, the Peen[illegible] [illegible] had a qualified electronic engineering section.

RADAR FROM THE VIEWPOINT OF THE AIR FORCES

The ability to achieve air force operations under all conditions of darkness and weather contributes more than any other single factor to increasing the military effectiveness of the air forces. Hence, any research program designed to overcome the limitations to flight at night and in bad weather will pay big dividends.

Radar has already done much to overcome visibility limitations, and is of the greatest importance in the problems of traffic control in and near airports and of landing under conditions of bad or zero visibility. Although there is room for great technical development of the radio and radar aids to landing and traffic control, one of the chief problems is the development of a system in which all conceivable aids will be properly integrated and used together. This can only come as a result of extensive experience and a comprehensive program of trials.

Radar has revolutionized methods of air navigation. The development of microwave radar, which permits the use of narrow beams, enables the continuous presentation to the navigator of a more or less recognizable map of the surrounding country. In its earliest and crude form little more than cities, towns, and coastlines could be distinguished; but modern developments give sufficient resolution to identify many features of the landscape such as rivers, streams, bridges, and rail lines and make feasible the use of ordinary maps. In addition, heavy storm clouds make themselves evident on the radar screen. Over the sea, radar contact flying is restricted to areas within sight of identifiable land, but radar "sees" at distances up to 50 or 100 miles.

The possibilities of direct radar navigation are greatly extended by the use of strong, readily identifiable, artificial echoes provided by radar beacons, the radar equivalent of optical beacons or lighthouses. Radar permits the measurement of distance to the beacon and its bearing within the inherent accuracy of the radar equipment carried on the aircraft. By measurements on two beacons, the position of the aircraft can be determined.

Microwave systems give essentially short-range navigation. For long ranges the pulse techniques of radar are applied to longer waves, for example, in the Loran system. Here two pairs of ground stations emit synchronized pulses. In the aircraft the pulses are received and the time difference between the arrival of the pulses from the members of a pair is measured. This locates the aircraft on a hyperbolic line of position and two such lines give a fix. The airplane carries only a receiver and the traffic capacity is unlimited.

The use of radar in strategic bombing operations has proved itself in this war. Suitable radar equipment can allow the carrying on of such operations under the many conditions where visual bombing is not possible. Only a beginning has been made in the development of radar bombsights and much remains to be done to improve their precision, their versatility, and over-all operational usefulness.

Tremendous improvement in the control and marshalling of air forces appears possible through the medium of airborne radar. Control of air operations includes military functions, involving radar surveillance of movements of friendly and enemy aircraft, and the guidance of our own planes on their missions.

The future development of control radar falls into two categories: radar for the defense of this country, and radar for attack. It is not necessary to say more about the defensive possibilities of ground-control radar. The problem of the future is chiefly an economic one; to install sufficient stations to surround the country completely is possible and necessary. Since these stations can be easily integrated into the airlines navigational net, the investment will be of great peacetime value. While in peacetime the network will be extremely valuable, in war it will be our protection against sneak attacks, and against air raids of all descriptions. Control radar for offensive warfare will undoubtedly develop to the point where a unified command of air operations is possible throughout the whole operation. The commanding general will see the disposition of his own and enemy forces, whether piloted or pilotless, and be able to instantly modify his plans.

Radar also has been used in aerial fighting for aircraft interception, for range finding, for tail warning, and for fire control, particularly in the defense of heavy bombers. Future developments of radar equipment for fighters are largely dependent on the extent to which it is found desirable to control fighters by ground equipment of increased range and resolving power. Fire control and associated radar equipment for heavy bombers can be made indefinitely more and more complex. An analysis to determine whether one should abandon such air battleships seems in order, before developing more complicated equipment which may only slow down the airplane to the point where still more and more complexity and fire power is needed.

The radically altered military situation produced by the development of guided missiles has been discussed previously. The development of radar and other detection and navigation devices has provided a wealth of technical means for locating and guiding missiles. The essential problems which radar can solve are those of locating the missile, locating the target, and transferring intelligence to and from the missile. The present fundamental limitation is that the missile cannot be followed over the horizon. This limitation has to be circumvented by providing one or more relay stations, putting the controlling radar in an aircraft, or by shifting the location problem to the missile itself. Long-range guidance will be combined with homing devices for attack against certain targets, for example, ships.

The application of radar to guided missiles brings in new problems because of the large scale on which missile warfare must be planned. Radar components of much simpler design must be developed.

Most of the problems mentioned above require, before all, engineering skill and talents for clever adaptation and combination of recently developed principles and methods. However, the art of radar is so new that limitations which appear today may soon disappear because of novel discoveries. The Air Forces must be alert in swiftly utilizing any new developments.

The military applications of infrared and heat radiation are for (1) sig[illegible]lling, (2) identification, (3) detection, (4) communication, and (5) guiding of heat-[illegible]ming missiles.

GERMAN DEVELOPMENTS

At the onset of the war, the Germans assumed that the Allies would employ [illegible]fra-red equipment and consequently produced in limited quantity a simple phosph[illegible] in-frared detector as a countermeasure. These instruments were very insensitive com[illegible]red with the U. S. phosphor developed somewhat later in the war. Although wor[illegible] [illegible]on-tinued in Germany, apparently it did not lead to improved instruments.

Very intensive work was done in Germany on the development of electron [illegible] [illegible]ge tubes. However, this work was not unified and there appears to have been consid[illegible]ble duplication of effort and lost motion due to a lack of full interchange of inform[illegible]on. The performance of the tubes was quite good but none of the designs was suita[illegible] for large quantity production. Furthermore, instead of concentrating on the manuf[illegible]re of one type, they attempted to produce four or five different types. The telescope[illegible]ed with the image tubes were elaborate and complex in the extreme; for exampl[illegible] [illegible]ne driving and gunsighting telescope had 17 glass elements mounted in a str[illegible]re weighing more than 25 pounds. Because of this, German produc[illegible] was onl[illegible]st getting started at the close of the war. A total of 1000 to 3000 units was built, [illegible] [illegible]l-most none of these ever saw combat duty.

The Germans appeared not to have developed a signalling and identific[illegible] system using tholofode cells. In the field of infrared communication equipment ([illegible] phones), the Germans were somewhat ahead of the Allies in that they had at least [illegible] units in field service. These units are not technically superior to the developmental models built in the United States.

The German work in the far-infrared field (heat) was not very extensive, the only work reported so far being a number of ship-detecting units for detecting and [illegible]ter-mining the range of ships off shore.

ALLIED DEVELOPMENTS

The British concentrated work on a simple electron image tube suited prin[illegible]ily for signaling and identification, although it was used experimentally for such purposes as driving, gun aiming, etc. Production started about 1941 and the instruments were used on the British Isles throughout the war. For security reasons, few were use[illegible] on the Continent but some, together with a few U. S. instruments, were used in N[illegible]th Africa.

U. S. production of image tubes and telescopes was not started until 1942 [illegible]nd they were not produced in quantity until a year later. Their first use in large num[illegible]ers was by the Navy for signal communications. Later the Army put into the field a gun-sighting and reconnaissance unit. These were used almost exclusively in the Pacific.

Airborne applications have been found practical but the various technical difficulties were overcome too late for field use. Detection of aircraft by infrared telescopes was found not to be feasible.

No communication systems for speech transmission were put into production.

Very extensive work has been done on heat sensitive elements for guided missiles, the production in some instances running into fairly large figures. Recent tests of the VB6, a heat-homing missile developed by NDRC Division 5 in collaboration with ATSC, have been very successful.

The possibilities of infrared and heat-seeking devices are certainly not yet fully explored. It will be one of the important research fields of the Air Forces. The importance of this branch of physical research will be enhanced by the fact that many industrial and military establishments will try to obtain relative safety by going underground.

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ABSTRACT:

Developments and possibilities in supersonic flight, pilotless aircraft, propulsion methods (including atomic energy, jets, and rockets), tailless aircraft, radar, and infrared radiation are summarized. More supersonic wind-tunnel and flight-test research is recommended along with study of supersonic launching and landing problems, winged guided missiles, and heat-seeking devices. Flow measurement techniques, laminar flow, and boundary layer control are also discussed. Diagrams, charts, and Schlieren photographs present empirical and theoretical data regarding these subjects.

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